GEOLOGICAL SURVEY OF CANADA

OPEN FILE 4679

Paskapoo-Porcupine Hills Formations in Western Alberta: Synthesis of Regional Geology and Resource Potential

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2004

Available from
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2004: Paskapoo-Porcupine Hills formations in western Alberta: Synthesis of regional geology and resource potential; Geological Survey of Canada, Open File 4679.

INTRODUCTION

Paskapoo Formation

The Paskapoo Formation and its equivalents represent an important emerging interval of bedrock strata with significant resource potential in western Alberta, where population, agricultural and industrial pressures are mounting. In the early part of the 20th Century, it supplied much of the building stone to create the gracious structures of a young province; for decades, it has provided much of the groundwater for the western part of the province; and with the dawn of a new century, the Paskapoo is now an exploration target for the shallow gas industry. The time is propitious for a review of the state of knowledge of these rocks, and to utilize this background as a launchpad for further studies.

Because the Paskapoo represents the bedrock at surface over its area of occurrence, and has not previously been a major hydrocarbon target, there has been little application of subsurface data and techniques to its study. Even outcrop studies have been limited and few. However, there is now an opportunity to exploit the superb WCSB subsurface data base in developing an integrated understanding of the true stratigraphic and sedimentologic evaluation of this bedrock groundwater aquifer/shallow gas system, partly through synthesis of vast existing data sets and partly through new geological work in outcrop and subsurface. Some of this work might even relate to the topics of geothermal energy, waste disposal reservoirs, aquifer contamination, and fuel for hydrogen generators in the future. Useful techniques include careful study of outcrop analogies, log correlation, subsurface mapping, facies modelling, detailed delineation of porosity/permeability variation, diagenetic effects on petrophysical properties, detailed mapping and prediction of aquifer geometry, shallow seismic, sophisticated drilling, and studies of fluid migration paths and trapping.

Acknowledgements

The following report has benefited from numerous discussions with Art Sweet, who also reviewed an earlier version, and provided many suggestions for improvement. Paul Wozniak compiled and drafted the figures.

GENERAL TECTONIC AND DEPOSITIONAL SETTING

Foreland Basin Basics

In the Western Canada Sedimentary Basin (WCSB) the first-order foreland basin succession is the second of two major eastward-thinning wedges. It is approximately equivalent to the Zuni Sequence of Sloss (1963), comprises about 45% of the sedimentary rocks in the WCSB (Lennox, 1993), and is a direct result of the evolution of the Canadian Cordillera during Jurassic to Paleocene time (Porter et al., 1982). A foreland basin is an asymmetric sedimentary basin which develops between the deforming mountain front and the adjacent craton, where a great volume of orogen-derived sediment can accumulate in an active tectonic setting (Allen et al., 1986). It forms by downward flexure of the lithosphere in response to thrust loading at the convergent margin (Beaumont, 1981).

The Canadian Cordillera consists of a tectonic collage of allocthonous terranes (Monger, 1989). Collisional accretion of microcontinents to the western margin of ancient North America compressed and detached the underlying Paleozoic miogeoclinal wedge, and telescoped and translated these strata as imbricate thrust sheets to form the thickened orogenic belt (Porter et al., 1982; Price, 1994).This thrust sheet load flexed the crust to form a deeply subsiding asymmetric foredeep, which migrated in front of the advancing thrust stack, and provided the source of detritus deposited into that foredeep (Beaumont, 1981; Price, 1994). This led to a dramatic reversal of sediment dispersal, from generally westward off the craton, to generally eastward off the orogen as the miogeoclinal and earlier molassic strata were cannibalized. An enormous volume of synorogenic shallow marine and nonmarine sediments were deposited in asymmetric, generally regressive clastic wedges as a result (Leckie and Smith, 1993). Stratigraphic sequences in foreland basins are clearly controlled by regional tectonism, as evidenced by variation in sediment source, depositional regime and uplift/subsidence patterns between successive sequences (Embry, 1990; Miall, 1991; Eberth and Hamblin, 1993; Hamblin, 1997).

Laramide Orogeny and Basin Infill

In mid-Cretaceous time a change from orthogonal to oblique northward convergence, caused western parts of the Cordillera to be displaced hundreds of kilometres to the north (Monger, 1989). Late Cretaceous (Turonian/Cenomanian) docking of the oceanic Insular Superterrane (Alexander/Wrangellia Terranes), and others, (Monger, 1989; Cant and Stockmal, 1989; Stockmal et al., 1993; Price, 1994) led to overthrusting of supracrustal rocks, rapidly intensifying tectonic loading, foredeep subsidence (creating accommodation space) and cannibalization of previous deposits. This resulted in rapid deposition of a series of generally regressive wedges of marine to nonmarine synorogenic molassic sediments during the Campanian to Paleocene (Jerzykiewicz, 1985). This second-order composite coarsening-upward succession, up to 2.5 km thick, was deposited during 20-25 m.y. (sedimentation rate of about 175 m/m.y.) and represents the final stage of foreland evolution (Porter et al., 1982) and the last portion of the Zuni Sequence of Sloss (1963).

Cant and Stockmal (1989) and Chamberlain et al. (1989) noted the typical lag time between the increase in subsidence and the increase in sediment supply (here, up to 20 m.y. between Superterrane docking and the appearance of coarse clastic detritus in the preserved portion of the foreland; Underschultz and Erdmer, 1991), creating generally coarsening-upward successions. This last portion of the Zuni Sequence (Sloss, 1963; Porter et al., 1982) represents an eastward-thinning wedge which extended into Manitoba (Taylor et al., 1964; Dawson et al., 1994) but was later partially eroded after thrusting ceased and crustal extension began in Eocene time (Monger, 1989), leaving only erosional remnants over the Plains. Environments of deposition are generally nonmarine to the west and marine to the east (where preserved) and characterized by successive transgressive-regressive cycles (Leckie and Smith, 1993; Dawson et al., 1994). Subsidence and sedimentation rates relate directly to geographically limited tectonic loading and creation of accommodation space, and resulting sediment dispersal patterns. Most sediment was supplied through cannibalization of earlier Paleozoic/Mesozoic sediments from the emerging Rockies (Rahmani and Lerbekmo, 1975; Porter et al., 1982; Stott, 1984; Jerzykiewicz, 1985; Mack and Jerzykiewicz, 1989).

Regional Upper Cretaceous-Tertiary Internal Stratigraphy

The second-order composite portion of the Zuni Sequence (Sloss, 1963; Porter *et al.*, 1982) in the Plains (termed the "post-Colorado" section) represents an eastward-thinning prism originally up to 2.5 km thick, or more, which extended into Manitoba (Dawson et al., 1994). It was later partially eroded as crustal extension began in the Eocene (Monger, 1989; Price, 1994). Probably no major arches were active (although Lorenz, 1982, suggested that uplift of the Sweetgrass/Bow Island Arch was related to Laramide thrusting) and most sediment was supplied through cannibalization of earlier Paleozoic/Mesozoic strata from the emerging Rockies (Rahmani and Lerbekmo, 1975; Porter et al., 1982; Stott, 1984; Jerzykiewicz, 1985; Mack and Jerzykiewicz, 1989; Price, 1994).

The post-Colorado succession is an overall coarsening-upward succession (Jerzykiewicz, 1985). At least five major sandy clastic wedges related to orogenic pulses are present, representing infill of the foreland basin controlled by variable rates of tectonic subsidence (Jerzykiewicz, 1985; Mack and Jerzykiewicz, 1989). Jerzykiewicz and Labonte (1991) and Leckie and Smith (1993) noted that prevailing drainage in the proximal part of the foreland is perpendicular to the basin axis in overfilled phases and parallel to the basin axis in underfilled phases.

In the Late Cretaceous, a N/S-trending broad inland seaway existed between the Canadian Shield and the active Cordilleran belt (Stott, 1984) stretching from the Arctic to the Gulf of Mexico, generally with N/S, NW/SE or NE/SW shoreline trends (Rosenthal, 1984). Environments of deposition were generally nonmarine to the west intertonguing with marine to the east (where preserved) (Leckie and Smith, 1993; Dawson *et al*, 1994). These reflect a series of stacked transgressive-regressive cycles (Dawson et al., 1994), with less marine influence through time. By the end of the Zuni Sequence, all deposition was nonmarine. The climatic conditions were warm-temperate to subtropical, and semi-arid to increasingly humid northwards (Jerzykiewicz and Sweet, 1988).

The strata of this second-order succession are subdivided into five main sandstone-dominated depositional assemblages (Fig. 1). These are:

1) Lower Campanian Milk River Formation (and equivalents) shallow marine and shoreline, with minor fluvial, deposits;
2) Middle to Upper Campanian Belly River (Judith River) Group (and equivalents) fluvial, shoreline, estuarine and shallow marine deposits;
3) Upper Campanian to Lower Maastrichtian Horseshoe Canyon Formation (and equivalents) fluvial, shoreline and shallow marine deposits;
4) Upper Maastrichtian to Lower Paleocene Scollard Formation (and equivalents) fluvial deposits;
5) Middle to Upper Paleocene Paskapoo Formation (and equivalents) fluvial deposits.

In general, these sandstone-dominated depositional assemblages form the primarily regressive, nonmarine portions of third-order successions and are separated by marine tongues (between lower wedges) and regional unconformities (between upper wedges) (Fig. 2). Each successive clastic wedge is dominated more by continental facies and less by marine facies.

Within earlier assemblages, higher order transgressive-regressive cycles are very important on local scales, and were likely controlled by variations in the interaction of tectonic subsidence and sediment supply.

In the central Foothills, six coarsening-upward cyclothems, related to orogenic pulses, were identified in this succession(Jerzykiewicz, 1985): the Paskapoo/Porcupine Hills strata correlate to his Cycle VI. Mack and Jerzykiewicz (1989) suggested that three main periods of thrusting are signalled by the sediments of the Belly River, lower Willow Creek and Paskapoo units in the Foothills, separated by two periods of relative tectonic quiescence represented by the St. Mary River and upper Willow Creek sediments. In general, Campanian subsidence and sedimentation rate increased markedly in southwestern Alberta, but decreased northward (Hamblin, 1997), whereas in the Maastrichtian, these rates increased markedly in northwestern Alberta and decreased progressively southward (Chamberlain et al., 1989; Hamblin, 2004). These effects presumably relate directly to geographically limited tectonic loading and creation of accommodation space, and resulting sediment dispersal patterns. Environments of deposition are generally nonmarine to the west and sediment-starved marine to the east (where preserved) (Leckie and Smith, 1993).

The Paskapoo-Porcupine Hills Succession

The Paskapoo-Porcupine Hills formations of the Plains and Foothills collectively represent a vast eastward-thinning wedge of nonmarine sediments deposited into the mature WCSB from the rising Cordillera. During the Late Cretaceous, a major north-south, broad inland seaway had existed between the Canadian Shield and the active Cordilleran belt, stretching from the Arctic to the Gulf of Mexico (Stott, 1984). During the latest Maastrichtian to earliest Paleocene, this marine realm, now of only Gulfian affinity (“Cannonball Sea”), had withdrawn to the distal reaches of the WCSB in Manitoba and North Dakota (Stott et al., 1993), leaving the nonmarine environments of this third-order sequence hundreds of kilometres from the shorelines. This third-order sequence records renewed high energy sedimentation associated with the Laramide Orogeny, including alluvial fan and fluvial floodplain environments, and the final stage of foreland evolution. It is analogous to the molasse facies which borders the European Alps (Carrigy, 1971). Much of the sediment was supplied through cannibalization of earlier deposits and up to 3000 m of continental clastic sediments were shed from the orogen into the foreland (Porter et al., 1982; Stott et al., 1993). Volcanic detritus was derived from rocks in the interior of B.C. and Montana, and chert was derived from the Paleozoics of the Rockies thrusts (Carrigy, 1970). The Laramide Orogeny began during the Late Cretaceous, continued through the Paleocene and terminated during the Eocene when Cretaceous and early Tertiary strata were involved in deformation of the Foothills (Stott et al., 1993; Price, 1994). The dominant transpressive regime, which had been characterized by compression in the south, thrusting and strong subsidence in the foreland basin, ended at about 58 Ma as convergence between the accreted terranes and the craton waned (Price, 1994). The supply of detritus was greatly reduced and that regime was replaced by one of isostatic uplift and erosion in the basin in mid-Eocene time, creating the regional post-Zuni erosional unconformity and peneplain, at or near the present-day land surface, which caps the Paskapoo-Porcupine Hills third-order sequence (Price, 1994; Dawson et al., 1994; Stott et al, 1993). Whereas Upper Cretaceous and Paleocene units had been involved in the Laramide deformation, the minimum age for that deformation is given by the overlapping deposition of the Eocene-Oligocene Kishenehn Formation into a graben which postdates the Laramide Lewis Thrust (Stott et al. (1993). In the Plains, the strata are near-horizontal, dipping westward at <1° as a homoclinal wedge into the core of the Alberta Syncline. Relatively few long outcrops, cores or geophysical logs are available for study of these strata, and those are widely scattered stratigraphically and geographically.

Cycle VIa of the central Foothills occurs at the top of an overall coarsening-upward succession representing infill of the foreland basin controlled by tectonic processes (Jerzykiewicz, 1985). The equivalent Paskapoo of the Plains comprises part of a vast eastward-thinning wedge of fluvial sediments, the late-stage foreland infill, which extended from the Paleocene deformational front to Manitoba (Taylor et al., 1964; Gibson, 1977; Dawson et al., 1994). The deposits of this sequence are exclusively continental. A small body of paleocurrent data indicates general northeastward dispersal (Jerzykiewicz and Labonte, 1991) whereas, mineralogical analysis by Rahmani and Lerbekmo (1975) was interpreted to suggest a regional east or southeast flowing fluvial system in western Alberta. The bulk of sedimentary detritus was provided by cannibalistic erosion of Phanerozoic sediments in the ancestral Rockies, indicating major tectonic uplift of this source area (Rahmani and Lerbekmo, 1975; Mack and Jerzykiewicz, 1989).

According to Jerzykiewicz (1985) and Mack and Jerzykiewicz (1989) the later portion of the underlying Scollard/Willow Creek clastic wedge was deposited during a phase of tectonic quiescence with finer grained deposits and coals (Cycle Vb). However, this was followed by reactivation of thrusting, in the eastern Main Ranges or Front Ranges, to start Paskapoo deposition (Mack and Jerzykiewicz, 1989). The facies present and their distribution indicates that the rate of basinal subsidence was not uniform through time (Jerzykiewicz, 1985). Deposition occurred in an actively subsiding foreland basin with greater rate of subsidence to the west, as shown by the distinctly asymmetric wedge-shape, with greater thickness of Paskapoo-age sediments to the west (Jerzykiewicz, 1997). The lower part of the clastic wedge is dominated by coarser clastics and sedimentary rock fragments, with a concomitant decrease in metamorphic and volcanic fragments, suggesting that thrusted Paleozoic and Mesozoic rocks supplied the detritus (Mack and Jerzykiewicz, 1989). The upper part, where preserved, is dominated by finer grained sediments with coal.

STRATIGRAPHIC SUMMARY

Paskapoo Formation

The Paskapoo Formation comprises light grey, buff-weathering, thick bedded sandstone and grey to greenish sandy mudstone and siltstone, deposited in nonmarine environments. It has traditionally been correlated to the Porcupine Hills Formation of southwestern Alberta, the Ravenscrag Formation ("buff facies") of southern Saskatchewan, and the Fort Union Formation of Montana and North Dakota, although there is little precise data for the latter two correlations. The relation of the Paskapoo and Porcupine Hills formations is more fully discussed below. The Paskapoo was initially described by Tyrrell (1887), based on a series of discontinuous outcrops along Red Deer and Blindman rivers near the city of Red Deer, to include all beds below the

Miocene gravels and above the "Big Seam" at the top of the Edmonton Group (ie. Ardley Seam of the Scollard Formation) (Allan and Sanderson, 1945). Allan and Sanderson (1945) provided further definitive details, including the coarser grain size and lack of bentonite in Paskapoo rocks compared to underlying Edmonton rocks. It has an erosional base with thick sandstone beds overlying the Ardley Coal Zone, and its upper limit is the land surface, except on localized plateaus where younger Tertiary gravels are present. Lerbekmo et al. (1992) demonstrated that the basal contact is a regional unconformity, an idea first proposed by Allan and Sanderson (1945). There are no continuous outcrop sections exposing the entire unit, which is up to 850 m thick (Jerzykiewicz, 1997). The erosional remnants represent the preserved part of an originally thick extensive clastic wedge which disconformably overlies the Scollard-Willow Creek sequence. Paskapoo, and underlying upper Scollard strata, are well exposed on Bow River and Jumpingpound Creek near Cochrane, at Bearspaw Dam and Fish Creek Park and Edworthy Park in Calgary, and on Red Deer River near Tolman Bridge and the city of Red Deer.

Early authors (Williams and Dyer, 1930; Allan and Sanderson, 1945; Irish, 1970) included the Scollard as a member of the Paskapoo. Carrigy (1970, 1971) placed the lower boundary of the Paskapoo at the top of the Battle Formation, including the Scollard in the Paskapoo, and suggested that the Porcupine Hills is younger than the Paskapoo, but these ideas are not now accepted (Krause, 1978; Fox, 1990). Later, Gibson (1977) redefined the Scollard as part of the Edmonton Group. Gibson (1977) and Lerbekmo et al. (1990) stated that the Paskapoo overlies the Scollard with local erosional topography (due to channelization) of up to 25 m, although only a minor time hiatus is represented.

Demchuk and Hills (1991) provided the first organization of the internal stratigraphy of the Paskapoo Formation by defining three members on Red Deer River in the central Alberta Plains, in ascending order: the Haynes, Lacombe and Dalehurst Members. The first and second were established through reference to several long continuous cores drilled by Alberta Research Council in the Red Deer area, and additional local outcrops. In general, in the Plains, the Paskapoo displays an overall fining-upward trend and is dominated by recessive, fine grained strata (Demchuk and Hills, 1991). Descriptions, summarized from the work of Demchuk and Hills (1991) follow.

The Haynes Member is characterized by cliff-forming, stacked, thick medium to coarse grained sandstone beds sharply overlying the fine grained upper Scollard Formation. The sandstones are light grey (salt and pepper), weather a buff colour, are characterized by sharp bases with conglomeratic lags, trough crossbedding and minor ripples, and roots and plant fragments are common. Lesser interbeds of grey or greenish siltstone and mudstone are common. These strata lie on a regional unconformity surface representing a hiatus of about 1-2 m.y. in the type area (Lerbekmo et al., 1990, 1992; Lerbekmo and Sweet, 2000). The type section is designated in A.R.C. Corehole 2-82 (4-6-39-24W4) from 56.5-108.5 m and a reference section at Ardley Bend. The overlying Lacombe Member is characterized by interbedded grey to green siltstone, mudstone, thin argillaceous coals and minor fine grained sandstone. Plant fragments and pedogenic features are ubiquitous. According to the authors, the Lacombe Member nominally includes most of the strata of the Paskapoo Formation, although no outcrops or subsurface sections outside the main study area were examined in detail. Consequently, over most of the Paskapoo outcrop area, it is implied that this member is exposed at surface. The type section is designated in A.R.C. Corehole 3-82 (2-13-40-26W4) from 44.5-155.0 m and reference sections upstream from Joffre Bridge through to Blindman River near its confluence with Red Deer River. The youngest Dalehurst Member, characterized by interbedded fine grained sandstones, grey mudstones and at least five thick coal seams, is only preserved as an erosional remnant in the Hinton area. Siltstones are greenish to black, contain abundant plant fragments and pedogenic structures and coal seams are up to 6 m thick. Strata of the Dalehurst Member may be slightly younger than those of the Lacombe, but may, in part, be coeval with uppermost strata of the Lacombe. The type section is designated in Unocal Corehole 76-54 (7-8-53-24W5) from 17.5-143.0 m and reference sections in the Obed-Marsh mine.

In contrast to the subdivisions of Demchuk and Hills (1991), Jerzykiewicz (1997) harkened back to the division referred to by Carrigy (1970) as the Paskapoo-Porcupine Hills boundary, suggesting that separation of two distinct units is possible and is represented by his division between informal lower and upper members of the Paskapoo. To the north, Jerzykiewicz (1997) suggested that the base of his upper subdivision is marked by the High Divide Ridge conglomerate, and to the south, by escarpment-forming thick sandstones. These differing stratigraphic organizations need to be resolved in future.

Porcupine Hills Formation

The Porcupine Hills Formation was named by Dawson (1883) with the type section in the Porcupine Hills of southwestern Alberta where it was described as gradationally overlying the Willow Creek Formation (Williams and Dyer, 1930). Conversely, Braman and Sweet (1990) and Jerzykiewicz (1997) suggested that the thick basal sandstone of the Porcupine Hills disconformably overlies a paleosol horizon in the Willow Creek. Until recently, it was generally believed that the Porcupine Hills and Paskapoo formations were essentially equivalent, a correlation first made by Tyrrell (1887) and confirmed by Tozer (1956). Jerzykiewicz (1997) essentially suggested that the Porcupine Hills is simply an arid-climate facies of the Paskapoo. Recent magneto- and biostratigraphic work in the Calgary area by Lerbekmo and Sweet (2000) suggested that the lowest part of the Porcupine Hills is equivalent to the upper Scollard and the rest is Paskapoo-equivalent, with a significant hiatus between. This hiatus is equivalent to the base-of-Paskapoo erosional surface in the Red Deer River Valley (Lerbekmo and Sweet, 2000). The Porcupine Hills is up to 1220 m thick (Glass, 1990). The formation generally consists of recessive-weathering mudstone, characterized by well developed paleosols, with thick cross bedded sandstone beds. Sandstones range up to 15 m thick and carry a heavy calcareous cement, producing the prominent ridge of outcrops which give the unit its name (Tozer, 1956; Glass, 1990). Jerzykiewicz (1997) recognized informal upper and lower members, defined by a prominent and laterally extensive sandstone layer, which he correlated to similar deposits at the base of his upper Paskapoo to the north.

Ravenscrag Formation

Strata which may be equivalent to the Paskapoo and Porcupine Hills formations are present in the Cypress Hills of southeastern Alberta-southwestern Saskatchewan. The type section of the Ravenscrag Formation is at Ravenscrag Butte, Saskatchewan (Furnival, 1950) and it was originally defined to include the Frenchman Formation, resting disconformably on the

Battle Formation of the Edmonton Group (Williams and Dyer, 1930; Russell and Landes, 1940). Braman (1990) points out that current usage in Saskatchewan has the base of the Ravenscrag at the top of the Frenchman Formation (ie. the Cretaceous-Tertiary boundary) as Furnival (1950) originally defined it, and therefore includes some upper Scollard-equivalent strata as its lower lignitic portion ("grey facies" of Furnival, 1950).

Only the upper sandstone-dominated "buff facies" (Furnival, 1950) is potentially equivalent to the middle Paleocene Paskapoo Formation (McIver and Basinger, 1997). The buff facies comprises about 30 m of dominantly fine grained sandstones and siltstones, with minor, poorly-developed coal seams and rarer plant fossils (Furnival, 1950; McIver and Basinger, 1997). Fluvial channel fill deposits are common, with coarser sand than in underlying units, suggesting less sinuous channels (McIver and Basinger, 1997). Part of the upper Ravenscrag is typically missing by erosion beneath the regional unconformity which caps the succession, hence outcrops of the Paskapoo-equivalent "buff facies" are limited. In places, the Oligocene Cypress Hills conglomerate directly overlies the Frenchman Formation, clearly showing that the Ravenscrag was completely eroded away (Furnival, 1950).

Distribution and Thickness

According to Taylor et al. (1964), Stott et al. (1993) and Dawson et al. (1994), the Paskapoo/Porcupine Hills clastic wedge comprised a continuous thick blanket, up to 3000 m thick in southwestern Alberta and thinning to about 90 m to the east, which was later eroded and dissected over much of its original area. It presently has wide distribution at surface over the trough of the Alberta Syncline in an outcrop band about 100 km wide, as well as scattered outliers preserved on Hand, Wintering and Cypress Hills (Allan and Sanderson, 1945). It represents an extensive floodplain deposit east of the Rocky Mountains (Meyboom, 1961) and is approximately equivalent to the Fort Union Formation of Montana and North Dakota.

Preserved thicknesses reported for the Paskapoo range from 750 m near Calgary (Allan and Sanderson, 1945; Meyboom, 1961; Glass, 1990), to a few tens of metres at Scollard Canyon east of Red Deer (Allan and Sanderson, 1945; Meyboom, 1961; Glass, 1990). In the southern Foothills, equivalent strata were named the Porcupine Hills Formation by Dawson (1883) and attain thicknesses of 1500 m on Oldman River (as quoted by Allan and Sanderson, 1945) or, more typically, up to 1000 m (Glass, 1990)

Paleoclimate

The Porcupine Hills has caliche glaebules in the mudstone facies, and common redeposited caliche nodules in channel lags (Braman and Sweet, 1990; also observed by myself in the Paskapoo in the Calgary area), suggesting a semi-arid to intermediate climate during deposition, at least in the south (Jerzykiewicz and Sweet, 1988). Conversely, coals are known in the upper Paskapoo in the north, implying a more humid climate in that area. Jerzykiewicz (1997) suggested that a gradual increase in seasonality through the Cretaceous and early Tertiary, enhanced by the withdrawal of the Interior Seaway, likely led to the pronounced north-south climatic trend present in these sediments, and still evident today. McIver and Basinger (1997) interpreted climatic conditions from the flora of the Ravenscrag Formation: a mesothermal humid climate without a dry season, light or absent frost, moderate to abundant precipitation, mean temperature of 15°C.

Paleontology

The Paskapoo has long been assigned a Paleocene age. In 1926, Russell collected freshwater gastropods, leaves, bones and teeth from the base of a sandstone bed along the Elbow River in Calgary which yielded a Late Paleocene date (Russell and Churcher, 1972). Previously, a small but important vertebrate fauna had been collected on the Red Deer River in 1910 by Barnum Brown (Fox, 1990) but was misinterpreted as Cretaceous in age (Russell and Churcher, 1972). Williams and Dyer (1930), Furnival (1950) and Budrevics (1978) all describe the flora and fauna as nonmarine, similar to that of the Fort Union Formation in Montana, and representing a long depositional period ranging from about 50 to 60 Ma in age. No marine fossils have ever been recovered, although the Fort Union of North Dakota and Montana includes a marine tongue, the Cannonball Member.

By far, the most common megafossils in the Paskapoo are of plants: Hoffman and Stockey (1999) noted that more than 20,000 specimens, representing 28 taxa were recovered from the Joffre Bridge Roadcut locality alone. These include leaves, fruits, seedlings and whole plants of conifers, flowering trees, ferns and aquatic plants (Hoffman and Stockey, 1999). The fossils were recovered primarily from the Lacombe Member, comprising channel-abandonment and floodplain depositional environments (Hoffman and Stockey, 1999). Whitaker (2000) also noted well preserved leaf imprints and wood impressions, including examples of sequoia, beech, maple, poplar and gingko trees. The flora is dominantly coniferous and dicotyledonous and suggests a warm temperate, humid climate (Stott et al., 1993). Whitaker (2000) envisioned a landscape of temperate forests with a lush mixture of bush, forest, riparian and undergrowth vegetation. The Ravenscrag Formation of Cypress Hills has likewise yielded a diverse, primarily broadleaf and needleleaf deciduous and minor coniferous, flora, including canopy-level trees, sub-canopy shrubs and a swampy understory represented by ferns and horsetails McIver and Basinger, 1997). Most of the Ravenscrag taxa are most closely related to modern floras living in moist climates without freezing temperatures (McIver and Basinger, 1997). Coaly wood fragments and well-preserved deciduous leaf imprints are very common in interbedded fine sandstone and siltstone facies, and indicate a diverse flora (Williams and Dyer, 1930; Bell, 1965).

Palynological studies have identified a Paleocene floral assemblage which is similar to that described from the western United States, based on the *Momipites-Caryapollenites* phylogenetic lineage (Demchuk (1990). Strata immediately above the Cretaceous-Tertiary boundary belong to the P1-aged *Wodehousei fimbriata* Zone, and the P2-aged *Momipites wyomingensis* Zone, and are included in the upper Scollard-upper Coalspur-lowermost Porcupine Hills formations (Demchuk, 1990; Lerbekmo and Sweet, 2000). These strata are capped by a mid-Paleocene hiatal surface which represents a gap of 1-3 m.y. Strata of the Paskapoo-Porcupine Hills third-order sequence belong to the P3-aged *Aquilapollenites spinulosus* Zone, the P4-aged *Caryapollenites wodehousei* Zone and the P5/P6-aged *Pistillipollenites mcgregorii* Zone (Demchuk, 1990; Lerbekmo and Sweet, 2000).

The most common animal fossils are freshwater and terrestrial molluscs, mostly long-ranging genera: *Unio* and *Sphaerium* are the most common pelecypods; *Viviparus*, *Physa,* *Oreohelix* and *Valvata* are the most common gastropods (Williams and Dyer, 1930; Allan and Sanderson, 1945; Tozer, 1956; Stott et al., 1993; Whitaker, 2000). These typically occur as coquinas or lags at the erosive bases of sandstone beds (see Webb, 1996). Also common in these occurrences are reptile and mammal bone fragments and teeth, freshwater fish skeletons and insect wings and larvae (Budrevics, 1978; Hoffman and Stockey, 1999). Among the mammalian fossils, multituberculates, primates, insectivores and condylarths are important groups represented and the Red Deer area has proven to be particularly rich (Fox, 1990; Stott et al., 1993). Krause (1978) described a diverse assemblage of Plesiadapiform primate fossils from a number of mid to late Paleocene sites in Alberta, including the Calgary and Red Deer Valley regions, and concluded that they ranged from latest Torrejonian to late Tiffanian in age. Fox (1990) reviewed the mammalian material recovered to that point, including multituberculates, primates and condylarths and correlated these to the North American Land Mammal Ages established in western United States. Study of mammal bones has been active since the earliest studies and has recently yielded new results. Webb (1996) and MacDonald (2001) described collections of mammal jaws and teeth including the identification of the remains of key taxa *Plesiadapis rex* and *Ectocion cedrus*, which indicate an age of middle Tiffanian (Ti 3). A local Cochrane man discovered the jawbone of a new species of mole-like mammal in "float" by the Bow River (Calgary Herald, August 25, 1995). Paleocene mammal material from Alberta and Saskatchewan are the most northerly of Paleocene mammal fossils in the world, corresponding to a Paleocene latitude of about 54-59° N (Fox, 1990; Webb, 1996). Collection at several sites by myself yielded abundant pelecypods and gastropods, as well as crocodile teeth, turtle shell fragments and reworked ?dinosaur? bone fragments. In addition, collection by myself yielded an abundant, but limited, ichnofauna of ?*Scoyenia* and *Planolites* in some beds of this facies.

Age

Recent studies have employed a unique integration of detailed palynostratigraphic, mammal biostratigraphic, radioisotopic and magnetostratigraphic methods to more fully constrain the age of Paskapoo-Porcupine Hills strata.

Palynological study in recent years has established an approximate time line at the base of the Paskapoo/Porcupine Hills, marking the change from impoverished P1/P2 floras (upper Scollard/upper Willow Creek) to diverse P3/P4, middle Paleocene floras (Jerzykiewicz and Sweet, 1988; Braman and Sweet, 1990; Braman and Sweet, 1999; Lerbekmo and Sweet, 2000). Nichols and Ott (1978) established a basic floral scheme for Tertiary deposits in Wyoming, based on a *Momipites-Caryapollenites* phylogenetic lineage, which is also applicable in western Canada. Palynostratigraphic analysis by Demchuk (1990) identified 2 palynological zones in the upper Scollard, and 3 palynological zones in the exposed Paskapoo of central and western Alberta with early to late Paleocene ages. Upper Scollard strata recorded early Paleocene P1 and P2 ages. Within the Paskapoo, the *Aquilapollenites spinulosus* Zone includes strata of the Haynes Member and is of middle Paleocene P3 age (Nichols and Ott, 1978; Demchuk, 1990; Demchuk and Hills, 1991). The Lacombe Member encompasses the upper part of the *A. Spinulosus* Zone, the *Caryapollenites wodehousei* Zone and the *Pistillipollenites mcgregorii* Zone of middle to upper Paleocene P4/P5 age (Nichols and Ott, 1978; Demchuk, 1990; Demchuk and Hills, 1991). The Dalehurst Member occurs within the uppermost part of the *P. Mcgregorii* Zone, of upper

Paleocene P5/P6 age (Nichols and Ott, 1978; Demchuk, 1990; Demchuk and Hills, 1991).

Mammalian remains, abundant at many Tertiary localities in western Canada, can be compared to the well-established North American Land Mammal age scheme. Krause (1978) described a diverse assemblage of Plesiadapiform primate fossils from a number of mid to late Paleocene sites in Alberta, including the Calgary and Red Deer Valley regions, and concluded that they ranged from latest Torrejonian to late Tiffanian in age. The assemblages collected implied that the Porcupine Hills Formation (latest Torrejonian to earliest Tiffanian) is older than the Paskapoo Formation (middle to late Tiffanian) (Krause, 1978). Fox (1990) reviewed all the mammalian material recovered to that point and correlated these to the North American Land Mammal Ages established in western United States. He described representatives of Puercan 1 and 2 (Ravenscrag Formation, coeval with upper Scollard?), Torrejonian 2 and 3 (Coalspur and Porcupine Hills formations), and Tiffanian 2, 3 and 4 (Porcupine Hills and Paskapoo formations) ages (Fox, 1990). Study of mammal bones has been active since the earliest studies and has recently yielded new results. Webb (1996) described a collection of mammal jaws and teeth from a fluvial channel lag deposit near Drayton Valley which included specimens from 37, primarily aquatic, genera within 8 mammalian orders. Likewise, MacDonald (2001) recovered a diverse fauna at Hand Hills. Both studies identified the remains of key taxa *Plesiadapis rex* and *Ectocion cedrus*, which indicate an age of middle Tiffanian (Ti 3).

Lerbekmo et al. (1990, 1992) showed that the upper Scollard (P1-P2 palynological zones) records magnetic polarity zones 29r, 29, 28r and 28 (from base to top) in the Red Deer Valley-Ardley-Scollard Canyon area. Conversely, the lower Paskapoo (P3-P5 palynological zones and Ti3-Ti4 mammalian ages) includes zones 26r, 26 and 25r (from base to top) in the same area (Lerbekmo et al., 1990, 1992). These conclusions were constructed utilizing the detailed correlation of palynological, mammalian and magnetic data. Therefore, a significant hiatus encompassing part or all of magnetozones 28, 27r, 27, and 26r is present at that contact, and represents a gap of about 2-3 m.y., from 60.5-63.0 Ma (based on Harland et al., 1990). This hiatus, first suggested by Allan and Sanderson (1945), was interpreted as a regional disconformity which might be related to the distal withdrawal of the Cannonball Sea hundreds of kilometres to the east (Lerbekmo et al., 1990, 1992). This hiatal surface in the proximal area of the foreland forms the base of the third-order Paskapoo-Porcupine Hills sequence. Similarly, in Hand Hills, east of the Red Deer River, a major sub-Paskapoo disconformity was identified by Lerbekmo et al. (1995). In this area, however, the hiatus encompasses magnetozones 28r, 28 and 27r, suggesting a hiatus of about 2 m.y. and that it is slightly older than that in the Red Deer Valley. Far to the southeast, in North Dakota, the succession is characterized by continuos sedimentation with no known gap (Catuneanu and Sweet, 1999). These data may delineate the eastward-dipping mid-Paleocene tectonic terrestrial surface upon which the Paskapoo was deposited, which petered out into marine deposition 700 km away. Subsequently, using a similar multi-disciplinary integrated approach, Lerbekmo and Sweet (2000) extended this mid-Paleocene hiatus through the Calgary area (between 28r and 27r, about 1 m.y. gap from 62-63 Ma, based on Harland et al., 1990) and southward into the Porcupine Hills area where that hiatus appears to reside *within* the Porcupine Hills Formation. Further confirmation of this contention will clarify the relationships within this third-order sequence.

In summary, based on all the above studies, it appears that the Paskapoo-Porcupine Hills sequence, above the 1-3 m.y. mid-Paleocene hiatus, displays age designations of middle to upper Paleocene. These include P3, P4, P5 and possibly P6 (palynology), Ti3 and Ti4 (mammalian), and 27r, 27, 26r, 26 and 25r (magnetic) and approximately 62.5-58.5 Ma (radiometric). Jerzykiewicz (1997) had suggested that the basinwide boundary at the base of the lower Paskapoo-Porcupine Hills (mid-Paleocene hiatus) is approximately 63 Ma in age, and the basinwide boundary at the base of the upper Paskapoo-Porcupine Hills is approximately 60 Ma.

SEDIMENTOLOGY

Lithology

The Paskapoo Series was first described by Tyrrell (1887) as consisting of "...hard, light grey or yellowish, brown-weathering sandstone, usually thick-bedded, but often showing false bedding (cross bedding); also of light bluish-grey and olive sandy shales, often interstratified with bands of hard, lamellar ferruginous sandstone".

The continental quartzose sediments of this clastic wedge have rarely been studied sedimentologically but have been briefly described in many general reports. Although fine grained (vertical accretion) deposits dominate, the thick sandstone channel facies provide the most outcrops and may represent important, prolonged and extensive periods of fluvial deposition (Jerzykiewicz, 1997). In the central Foothills the Saunders VIa has a preserved thickness of 300 m and is dominated by trough crossbedded channel sandstone, but the base is locally marked by the thick, erosionally-based quartzite cobble High Divide Ridge Conglomerate (Jerzykiewicz, 1985). In the southern Foothills the Porcupine Hills Formation has a sharp erosional base overlain by thick crossbedded calcareous sandstone interbedded with bentonitic and caliche-bearing mudstone (Braman and Sweet, 1990) interpreted to represent an intermediate fluvial facies association (Jerzykiewicz and Sweet, 1988).

In the western Plains of Alberta the Paskapoo is characterized by buff-weathering, light grey to greenish thick bedded, calcareous quartz/chert sandstone, with interbedded light grey to greenish or brownish, soft, calcareous, sandy siltstone (Williams and Dyer, 1930; Allan and Sanderson, 1945; Glass, 1990). These are the typical lithologies of the Haynes Member of Demchuk and Hills (1991). The Paskapoo was originally interpreted as predominantly lacustrine deposition after Tertiary sediments in the western U.S., but was then recognized as subaerial fluvial floodplain deposits where shallow ponds were present (Williams and Dyer, 1930; Allan and Sanderson, 1945). The lower 100 m is particularly coarse grained and well sorted with conglomeratic lenses (Allan and Sanderson, 1945; Demchuk and Hills, 1991), and at Scollard Canyon, localized channel erosion overlain by 50 m of medium to very coarse sandstone removed about 1.25 Ma of underlying record (Lerbekmo et al., 1990).

Fluvial Sandstones

Jerzykiewicz and Norris (1992) described the fluvial strata of the lower Porcupine Hills at several outcrops in the southwestern Plains. Thick, cross bedded, medium to coarse grained channel sandstone units are laterally extensive (blanket-like in typical limited outcrops) and have basal, sharp erosional surfaces which cut down into, and are separated by, thick units of mud-dominated overbank strata. The channel units consist of vertically-stacked, trough cross bedded or IHS sandstone bodies, and probably represent an interconnected network of stable channels in a vertically aggrading (anastomosing fluvial) system. Limited paleocurrent data indicates paleoflow to the north-northeast.

The following description is summarized from Williams and Dyer (1930), Allan and Sanderson (1945), Meyboom (1961) and personal observation. The characteristic thick channel sandstone beds range up to 15 m, but are typically 5-10 m thick, and are lenticular, pinching out laterally over 100-150 m or more. They have sharp, erosional bases with lags of large siltstone rip-ups, pelecypod and gastropod shells, leaf and wood fragments and reptile/mammal bones and teeth. Grain size ranges from very fine to very coarse sandstone, but typically is fine to medium grained sandstone and there is commonly a slight fining-upward trend at the tops of units. The sandstones are generally uniform, well sorted, calcareous, with trough crossbedding, horizontal lamination, large low-angle lamination and minor ripple cross lamination at the tops. Zones of contorted lamination about 50 cm thick are common. A handful of paleocurrent measurements from trough crossbedding in the Calgary area yielded northeastward transport directions. Meyboom (1961) found that Paskapoo sandstones have an average porosity of 7%, good permeability and are good, but limited, aquifers. Fine grained units range up to 50 m thick, but in outcrop are more typically 1-5 m thick of blocky, sandy siltstone and thin very fine to fine sandstone. Calcareous concretions, local lenses of woody coal 2-10 cm thick, and thin gastropod-rich limestones are ubiquitous. Rarely, thin bentonites and thin lenses of laminated lacustrine claystone are present. Sandstone beds range up to 1 m, pinch out laterally over several tens of metres, have sharp or gradational bases and horizontal and ripple cross lamination. Sandstone : siltstone ratios are about 1:2-5. At some outcrops the sandstone bases have an abundant ichnofauna of limited diversity, including *Planolites* and ?*Scoyenia*.

Nonmarine Mudstones

The thick fluvial sandstones are interbedded with the predominant lithology of the sequence which is light grey to greenish or brownish, soft, calcareous, sandy siltstone and mudstone, with thin fine grained sandstone beds (Williams and Dyer, 1930; Allan and Sanderson, 1945). These fine facies form intervals several to several tens of metres thick between the major sandstone horizons (Jerzykiewicz, 1997), but are typically poorly exposed (Williams and Dyer, 1930). These deposits represent vertical accretion in a widespread floodplain setting of the dominant fine grained sediment load carried by the fluvial dispersal systems. Both fining-upward and coarsening-upward small-scale sequences are present (Jerzykiewicz, 1997). Fine grained lithologies include ripple cross lamination and wavy bedding, abundant plant fragments and a variety of pedogenic features such as rooting, slickensides, mottling and cutans (Demchuk and Hills, 1991). Clay is generally of a very low percentage (Allan and Sanderson, 1945). Thin stringers of caliche glaebules, and rare calcrete horizons are present in many outcrops, especially to the south (Jerzykiewicz and Sweet, 1988; Jerzykiewicz, 1997) and thin limestone beds with freshwater or terrestrial gastropods are known (Allan and Sanderson, 1945). Dark grey fossiliferous mudstones, of freshwater origin, and thin carbonaceous mudstones are uncommon accessory facies in some areas, and thick coal seams are known to the north (Demchuk and Hills, 1991; Jerzykiewicz, 1997).

Facies Domains

Jerzykiewicz (1997) suggested the presence of five geographically distinct "facies domains" in the Paskapoo-Porcupine Hills third-order sequence. From north to south these domains reflect different paleoclimatic conditions (increasing aridity to the south), differing ratios of overbank mudstone to sandstone channel facies and differing styles of fluvial deposition. These domains are as follows.

1) Smoky River Domain: dominated by lacustrine mudstone with abundant freshwater pelecypods, minor coal and minor thin crevasse splay sandstone beds,

2) Athabasca Domain: thick alluvial fan coarse clast-supported conglomerate and medium to coarse sandstone in the lower part, overlain by the 150 m thick Obed Coal Zone,

3) North Saskatchewan River Domain: dominated by thick lacustrine/overbank mudstone facies with broad, vertically stacked medium grained channel sandstones, reflecting a high subsidence rate,

4) Bow River Domain: dominated by thick occurrences of mudstone with, with thick fining-upward meandering channel sandstones, but lacking well developed paleosols or significant coal,

5) Porcupine Hills Domain: dominated by thick mudstone occurrences with well developed paleosols, no coal and laterally confined anastomosing channel sandstones or broad, multistoried braided channel complexes (Jerzykiewicz, 1997).

Depositional Environments

In general, all strata of this third-order sequence were deposited in nonmarine environments.

Jerzykiewicz (1997) visualized a range of settings from proximal conglomeratic alluvial fans directly related to thrust topography and activity in the west, to medial fluvial plain channel sandstones and overbank fines through much of the area, to distal plain lacustrine and swamp settings preserved in particular areas.

Paleocurrents

Carrigy (1971) provided the first set of paleocurrent data for Paskapoo and Porcupine Hills formations (in fact, one of the first data sets in Western Canada). Over 1100 measurements of trough cross bedding (mostly from the Porcupine Hills Formation, but also including Paskapoo, Ravenscrag and Scollard formations) clearly show transport from west to east, but suggest paleoflow in the Paskapoo was toward the southeast, whereas paleoflow in the Porcupine Hills was toward the northeast (Carrigy, 1971). Interpretation of this data is complicated by Carrigy's lumping of strata we now know as Scollard and lower Ravenscrag into this data set, although this error may not substantially alter his conclusions. These data may indicate that there were two dispersal systems in play during the early-mid Paleocene, one in southwestern Alberta with flow toward the northeast, and another in west-central Alberta with flow toward the southeast. Only further data collection can resolve this possibility.

The only other significant set of paleocurrent data for the Paskapoo is that published by Jerzykiewicz and Labonte (1991) from four locations in the Central and Southern Foothills. A total of 171 readings indicate nearly uniform northeastward transport, which these authors related to direct influence of uplift in the foreland basin thrust belt. Jerzykiewicz (1997) added an unknown number of readings to this database from four locations in the Plains area, suggesting significant longitudinal southeastward (and minor southwestward) transport in these more distal areas.

A collection of 128 paleocurrent measurements by myself from fourteen outcrops in the Calgary area yielded predominantly northeastward and southeastward flow directions from trough crossbedded channel sandstones (with wide scatter), and predominantly eastward and southward flow directions from ripple cross laminated overbank sandstones and siltstones (with wide scatter).

Rahmani and Lerbekmo (1975) interpreted their heavy mineral provinces to suggest northwest to southeast sediment dispersal over most of Alberta, except for the far southwest corner where northeastward dispersal was dominant.

Petrography

Taylor et al. (1964) characterized this clastic wedge as quartz- and chert-rich sediments deposited from the west, post-dating the last feldspathic detritus shed from central British Columbia (ie. Scollard Formation), which had been cut off as a source area by the Main Ranges uplift. The sedimentary rocks of the ancestral Rockies provided much of the detritus, especially in southwestern Alberta (Rahmani and Lerbekmo, 1975), including Paleozoic pebbles at the base of the wedge (Taylor et al., 1964). The sandstones are generally fine to coarse grained, salt-and-pepper, of uniform mineralogy, calcareous in most areas, bentonitic, and with grains irregularly-shaped and only slightly rounded (Williams and Dyer, 1930; Allan and Sanderson, 1945; Russell and Landes, 1940; Meyboom, 1961; Carrigy, 1970; Glass, 1990). Paskapoo sandstones tend to be slightly coarser than Porcupine Hills sandstones (Carrigy, 1971). Porosity ranges 1-35% in outcrop, but is generally 8-15% (Carrigy, 1971). Intraformational conglomerates are common (Williams and Dyer, 1930). The sediments are 80-90% quartz, 10% clay, with 10-20% calcareous cement, minor altered feldspar and sedimentary rock fragments (Allan and Sanderson, 1945). They are more calcareous and have more heavy minerals and fewer feldspar grains than older units (Allan and Sanderson, 1945). Carrigy (1970, 1971) found that the Porcupine Hills was more chert-rich, has more clastic carbonate grains, has less plagioclase and has fewer volcanic rock fragments than the Paskapoo, suggesting a source rich in Paleozoic sedimentary rocks, as opposed to a volcanic-rich source for the Paskapoo. However, most samples with a high content of volcanic rock fragments in Carrigy's (1971) study were actually taken from the Scollard Formation. Likewise, heavy mineral suites from the Paskapoo imply an immature assemblage derived from a volcanic source, contrary to the resistant, second-cycle stable grains of the Porcupine Hills (Carrigy, 1971). These mineralogical data, like the paleocurrent data, may imply two petrogenetically distinct source areas: one southern depositional system derived from the Paleozoic thrust sheets of the southern Cordillera (Porcupine Hills sediments), and another northern depositional system derived from a volcanic source in the central or northern Cordillera (Paskapoo-Ravenscrag sediments). The more volcanic-rich Paskapoo deposits, therefore, are more subject to diagenetic alteration, carbonate cements and development of interstitial clays (Carrigy, 1971). However, as with the paleocurrent data set of Carrigy (1971), interpretation is hampered by Carrigy's erroneous inclusion of Scollard and lower Ravenscrag samples with

Paskapoo results.

Meyboom (1961) recorded mineral distributions of 30% quartz, 40% chert, 30% weathered feldspar grains plus calcareous cement in the Paskapoo. Feldspars are usually highly decomposed (Allan and Sanderson, 1945). Mack and Jerzykiewicz (1989) provide the most up-to-date study of the petrography in the Foothills. They found that the Paskapoo in the central Foothills has 32% sedimentary rock fragments, 36% volcanic rock fragments, 31% metamorphic rock fragments and <1% plutonic rock fragments (including a total of 42% quartz and chert) suggesting major sediment sources in the Omineca belt and the ancestral Rockies. The Porcupine Hills Formation in the southern Foothills has 81% sedimentary rock fragments (especially carbonate and chert), 6% volcanic rock fragments, 12% metamorphic rock fragments and <1% plutonic rock fragments (including a total of 76% quartz and chert) suggesting a major sediment source in the Paleozoic/Mesozoic of the ancestral Rockies. The sharpest increase in the sedimentary detritus occurs at the base of the Porcupine Hills. The lack of plutonic input is significant.

Rahmani and Lerbekmo (1975) defined four internally homogenous heavy mineral provinces in the Scollard/Paskapoo slice with trends oriented northwest/southeast. These are the 1) zircon province (only in the far southwest), 2) epidote/clinozoisite province (about 50% of the sediments), 3) garnet/apatite/sphene province (about 35% of the sediments, very widespread), and 4) hornblende province (only in the far northeast).

ECONOMIC POTENTIAL

Shallow Gas

Play Definition

The Paskapoo Basal Sandstone conceptual play was defined and summarized by Hamblin and Lee (1997) to include all potential gas bearing pools and prospects in fluvial channel sandstones of the lower part of the Paskapoo Formation. The following material is taken from that report and included here, with minor updating. It occurs in a large area of western Alberta along the axis of the Alberta Syncline. The play area is defined on the west and southwest by the limit of deformation, and on the east, north and south by the outcrop belt of the unit. The upper part of the Formation is exposed at surface throughout western Alberta. The play is purely conceptual at present.

Geology

The Paskapoo-Porcupine Hills formations of the Plains (Paleocene age) are part of a thick and widely distributed, eastward thinning wedge of fluvial strata which originally extended from the Late Cretaceous/ Early Paleocene deformational front in western Alberta to Manitoba along the western margin of a marine seaway (Taylor et al., 1964; Dawson et al., 1994). The units now exposed at surface represent only the preserved portion of an originally continuous blanket up to 1750 m thick in southwestern Alberta and thinning to only 90 m thick in Manitoba (Taylor et al., 1964; Dawson et al., 1994). The base of the third-order sequence is disconformable (Lerbekmo et al., 1990) with minor erosional bevelling of underlying units to the east.

The lower Paskapoo is characterized by erosively-based thick channel deposits of calcareous, well sorted medium to coarse grained sandstone, with minor conglomerate lenses and thin mudstone interbeds (Williams an Dyer, 1930; Allan and Sanderson, 1945). Channels are typically multi-storied, 5-10 m thick and pinch out laterally over about 100-150 m. The sandstone potential reservoirs are commonly fine well sorted, uniform and trough crossbedded. A small body of paleocurrent data indicates northeastward dispersal (Jerzykiewicz and Labonte, 1991). Meyboom (1961) found that Paskapoo sandstones have an average porosity of 7%, with good permeability.

The very thick Paskapoo Formation is present at surface over most of west-central Alberta, with the thick lower sandstone units present in the subsurface from Townships 25-55, west of the Fifth Meridian, to the disturbed belt. The overlying and interbedded nonmarine fine grained deposits of greenish siltstone with paleosols, interbedded with minor silty, very fine grained sandstone would serve as the vertical seal for potential pools in fluvial channel stratigraphic traps. The source of hydrocarbons may be the underlying nonmarine, coal-bearing strata of the Scollard-Coalspur formations.

Exploration History

There are no discoveries to date in this purely conceptual play, although minor anecdotal evidence suggests that gas is present, even at surface.

Play Potential

Estimates of the potential for this very conceptual play are not yet possible due to the limited data available. The potential gas resources in this play will likely be found in very small, very low pressure pools.

Coal

The thick coal seams of the Obed-Marsh coal zone of the upper Dalehurst Member of the Paskapoo Formation, located near Hinton, Alberta are of significant economic interest. These strata are the youngest bedrock units in the WCSB, of P5 age (Demchuk 1990). These are amenable to large-scale strip mining, producing thermal coal representing about 1% of Canada's total production in 1987 (Smith, 1989). At Obed, six seams occur within a 150 m sequence of interbedded sandstone, siltstone and mudstone, of which the lower two are stratigraphically close and thick enough to be exploited (Smith, 1989). Seams range from 1.3 to 6.1 m in thickness (Demchuk and Hills, 1991) and yield high volatile C bituminous material which can be prepared (through reduction of ash content) for domestic and offshore thermal coal markets (Smith, 1989). Coals of the Paskapoo Formation are too shallow and of too low a thermal maturity to be of interest for coalbed methane potential (Dawson et al., 2000).

Building and Ornamental Stone

Historical Background

Sandstone of the Paskapoo Formation was used extensively and for many decades in the construction of numerous buildings in Calgary and Edmonton, lending their distinctive appearance to those cities, and many of which are now designated as Provincial and National Historic Sites (Parks, 1916; Stott et al., 1993). The Paskapoo sandstone was the most important building and ornamental stone of Alberta (Parks, 1916), especially in the years 1887-1915, when up to 15 quarries and adjacent workers' villages were active in the immediate Calgary area (Cunniffe, 1969). In the 1890's, half the tradesmen in Calgary were stonemasons (Cunniffe, 1969).

On November 7 1886, fire burned four hotels and eleven other significant commercial buildings in downtown Calgary, threatening the entire community. A new city ordinance demanded that sandstone quarried from the local Paskapoo exposures which form the bedrock in the region be used to rebuild the major structures, and Calgary became known as "The Sandstone City". In addition, the Provincial Legislature Building in Edmonton was constructed partly of Paskapoo sandstone in 1912. Much of the stone for these structures was quarried in the Bow River corridor from Calgary to Cochrane, until about 1914 when supplies dwindled and less expensive brick and limestone became more available (Parks, 1916; Cunniffe, 1969). Even today, local supplies of Paskapoo sandstone have been stockpiled in preparation for vital restoration work on Calgary's historic buildings, and for use in landscaping.

Stone Quality

Paskapoo sandstone, quarried from fluvial and splay sandstone bodies, was desirable because it was soft and easily carved for decorative pieces, as well as strong enough for structural purposes (Parks, 1916; Cunniffe, 1969). Thick beds with significant lateral extent could provide very large slabs for building purposes. The stone varies greatly in grain, lamination and colour, with blue, yellow and grey types most common (Parks, 1916). Paskapoo sandstone is about one-third quartz, one-third semi-decomposed feldspar and one-third dark volcanic minerals, lending it an attractive salt and pepper effect (Parks, 1916). The original material has a high content of calcite cement, the presence or absence of which determines hardness, and porosity ranges 13-22%, and averages 18% (Parks, 1916). Interestingly, only the superficial, weathered part of any quarry area was easily workable: the native cemented stone is too hard for easy carving and so each quarry had limited volume which was suitable for the desired building uses (Parks, 1916). However, conversely, Paskapoo sandstones nearly always harden on exposure after installation, allowing fine masonry work during construction, but good weathering characteristics with time (Parks, 1916; Cunniffe, 1969). Irregularity of bedding, local variations in grain size and lime content, and spalling upon weathering are several known negative characteristics of the rock (Allan and Sanderson, 1945). Parks (1916) suggested that the failure of the industry after 1915 was due to a combination of factors, such as limited volumes and variable quality, high quarrying and dressing costs, and increased competition from less expensive imported limestone.

Industrial Ceramic Clay

The nonmarine overbank mudstones of the Paskapoo and Porcupine Hills formations have significant, but variable, potential for ceramic applications (Stott et al., 1993). Several historical bricking operations were formerly located on the west and south sides of the city of Calgary, and were particularly active in the early decades of the 20th Century. At Brickburn (now Edworthy Park) the Crandell Pressed Brick Company turned out up to 45,000 high-quality enamelled bricks per day (Cunniffe, 1969). The following summarizes information contained in a report by Scafe (1999). Positive features of the Paleocene deposits include large areal extent, generally good drying character (depending on the ratio of illite to smectite), moderate to long firing ranges, and acceptable colours for structural clay and pottery. Plasticity and working properties are typically good, with an average of 23% tempering water and 8% drying shrinkage. However, some samples are difficult to extrude, may crack during drying, and have short firing ranges, demanding rigid quality control on all processes. In general, a high illite content promotes good extrusion and drying characteristics, whereas a high smectite content results in poor extrusion and cracking. In mudstones of these formations, kaolin averages 10-15%, illite averages 40-50% (up to 70%), smectite averages 25-45% (up to 75%), and chlorite ranges 5-15%, with minor calcite/dolomite. Because they commonly have rather high smectite values, they suffer from common cracking during drying.

HYDROGEOLOGY

Introduction

Water has always been a vital resource: its availability affects the growth of communities, success of agriculture and the location of industries (Foster and Farvolden, 1958). But, the demand for water has increased dramatically over time, not only as population increases, but on a per capita basis as well (Foster and Farvolden, 1958) as urbanization, irrigation and industrialization skyrocket. Even in water-rich Alberta, the uneven distribution of the resource, both surface and groundwater, creates shortages and potential shortages as demand and usage rise. If a groundwater supply is depleted then the welfare of all people and natural environments is adversely affected but, on the other hand, in an urban/agriculture/industrial setting this natural resource is already under development (Farvolden, 1961). The prime handicap to wise, efficient and sustainable development of hidden groundwater resources is the lack of basic scientific data (Foster and Farvolden, 1958).

The Western Canada Sedimentary Basin actually represents a single large-scale hydrogeological regime, generally permeable and interconnected, but with a variety of local complexities (Lennox, 1993). Flow direction is primarily from the high Foothills toward the low-lying Canadian Shield (Lennox, 1993), and within each aquifer, flow is mostly parallel to bedding, although flow in confining shale layers can be normal to layering, creating leakage between separate aquifers (Fitts, 2002). Lennox (1993) identified several major regional hydrostratigraphic units within the sedimentary succession of the WCSB, including the “upper clastic unit”, which yields a large proportion of the groundwater used in Alberta (Foster and Farvolden, 1958). This comprises the Jurassic to Tertiary clastic blanket which represents the first-order Zuni Sequence of Sloss (1963) and forms the bedrock at surface over much of the Plains. This succession of interbedded sandstone, siltstone and mudstone has generally low thermal conductivities and steep geothermal gradients, with sandstone conductivities generally greater than those of mudstone (Lennox, 1993). In WCSB about half of the groundwater produced is for agricultural use (virtually all for watering livestock), and the rest split among rural household (22%), industrial (15%) and municipal (11%) uses (Lennox, 1993). One of the first industrial uses of groundwater was extracting Paskapoo Formation water for use in secondary recovery efforts in the Pembina Oil Field of west central Alberta (Foster and Farvolden, 1958; Farvolden, 1961), and was one of the reasons the Government of Alberta established hydrogeology studies. In recent years, industrial use has increased greatly, especially in oil sands processing in the northeastern part of the province. Within this larger hydrostratigraphic bedrock unit, many more local studies, performed over many decades, have elucidated characteristics of the third-order Paskapoo sequence. Paskapoo basal sandstones, reliably yielding 20-40 g.p.m., are considered the best bedrock aquifers in WCSB, aside from Milk River sandstones (Foster and Farvolden, 1958).

Because most sandstones are heterogeneous and permeability varies dramatically normal to bedding, hydraulic conductivities tend to be anisotropic with higher values parallel to bedding (Fitts, 2002). In general, the geology determines the rock permeability and partially determines the yield (Tokarsky, 1977). Although most bedrock groundwater in Alberta is soft, due to the moderating influence of abundant bentonite, Paskapoo waters are more variable because there is much less bentonite (Foster and Farvolden, 1958; Farvolden, 1961).

Case Studies

One of the first and most comprehensive local studies was undertaken in the Pembina area (T 47-49, R 7-10W5) because large volumes of Paskapoo groundwater were being systematically developed and produced in the 1950's for industrial use, prompting rural users to question the effects on their supplies (Farvolden, 1961). There, the Paskapoo is 150-300 m thick, dominated by shale, but with a discontinuous basal sandstone horizon 15-30 m thick. Aquifer sandstones range from very fine to coarse grained, subround to round, quartz and chert grains, with a calcite cement: intergranular permeability varies with the degree of cementation, although some fracture permeability is present (Farvolden, 1958). Aquitard shales range from hard, arenaceous and calcareous mudstone to soft, plastic clay. Good wells are obtained where cumulative sandstone thickness is large, and especially where one or more thick sandstone horizons are encountered in a hole, rather than numerous thin beds (Farvolden, 1958). In some very productive areas, drilling circulation is lost upon penetration and wells have encountered 30 m of net sandstone in only 75 m of depth (Farvolden, 1958). Here, all aquifers are recharged by local precipitation indicating full hydrologic connectivity and equilibrium, even where sandstone lenses appear to be completely enclosed by shale: still, horizontal permeability is greater than vertical permeability (Farvolden, 1958).

Lenticular Paskapoo sandstones of varying thickness represent major aquifers in the Calgary area and have porosities averaging 7%, good transmissivity and are under considerable pressure (Meyboom, 1961). However, flow rates are a disappointingly low 10-25 l/min, and can not be relied upon for the high population densities of the City of Calgary (Meyboom, 1961). Tóth (1966) showed that thick sandstone units in the Paskapoo were lenticular and can undergo lateral facies changes to siltstone over short distances, making correlation and mapping difficult in the Olds area. He also found that both primary intergranular porosity of thick porous sandstone aquifers, and secondary fracture porosity of all rock types including non-porous mudstone confining layers were important in transmissivity. Therefore, near Olds, groundwater forms a hydrologically continuous body in the strata and can be produced from all lithologies, although some lenses have greater permeabilities than the average (Tóth, 1966). In that area, the first high-production zone is typically at the drift-bedrock interface, either in clean sand/gravel lenses lying on that surface, or in the immediately underlying fractured bedrock strata, especially adjacent to the eroded channels of Quaternary buried valleys (Tóth, 1966). In the nearby Three Hills area, where most water production is from depths of 100 m or less, high permeability is restricted to channel sandstones, thin sandstone lenses, coal seams and the drift-bedrock contact (Tóth, 1968).

In a study of the Red Deer area, LeBreton (1971) found that Paskapoo calcareous sandstones up to 30 m thick produced good quality water of the bicarbonate type and T.D.S of < 1000 ppm and relatively high iron content. In the Rocky Mountain House area to the west, Tokarsky (1971) found that moderately deep Paskapoo sandstone aquifers are capable of yielding high flow rates in excess of 2500 l/min of excellent quality water, with high transmissivity values. A more normal regional yield value is 100-500 l/min, due to lesser clean permeable sandstones or destruction of primary porosity by cementation (Tokarsky, 1971).To the north, at Wabamun Lake, Ozaray (1972) identified a hierarchy of bedrock aquifer types: 1) friable Paskapoo sandstones yielding 2250 l/min, 2) thick, porous Paskapoo sandstones yielding 450-2250 l/min, 3) regionally characteristic Paskapoo with interbedded sandstone and siltstone yielding 100-450 l/min, 4) Paskapoo dominated by shale with thin sandstone layers and fracturing yielding 25-100 l/min, and 5) unfractured thick shales yielding 5-25 l/min. He also noted that bedrock porosity was higher in areas of concentrated discharge, suggesting that the porosity may be controlled by tectonic fracturing or that intensive groundwater flow may help to maintain and increase porosity (Ozaray, 1972).

Gabert (1975) restudied the Red Deer area in more detail, and identified a basal Paskapoo interval of thick extensive permeable fine to medium grained sandstones about 100 m thick composed of several vertically and laterally overlapping/coalescing aquifer bodies each ranging 15-30 m thick by 10-15 km wide and separated by low permeability mudstone-rich zones. Medium grained, well sorted sandstones had the highest permeability, but that permeability varied vertically and laterally, and was highest in uppermost and lowermost parts of each body (Gabert, 1975). While these individual sandstones can be laterally continuous over areas of 150 km^2, in some areas these aquifers are replaced laterally by siltstone/shale facies. The unit designated as Sandstone No. 1 was identified as the most important aquifer in the Paskapoo. In addition, thinner lenticular sandstones of restricted extent in predominantly mudstone sections of the upper Paskapoo, in combination with Quaternary gravel sheets, formed important shallow aquifers (Gabert, 1975). A few fractured shale zones also produce water, although regional fracturing was considered to be of minor importance in this area (Gabert, 1975). All waters produced were of the sodium-bicarbonate type, and T.D.S. is generally less than 1000 ppm.

Tokarsky (1977), working at Iosegun Lake, noted that fracture permeability is dominant in coal aquifers and may be important in other aquifer types as well. Although Paskapoo aquifers are typically lenticular, some are traceable for many kilometres and yields of 100-500 l/min are standard throughout this area, with possible flows up to 2000 l/min (Tokarsky, 1977). In the Edson region, Vogwill (1983) pointed out that, although Paskapoo intergranular conductivity is low, the conductivity of the sandstones is enhanced by fracture permeability from surface to a considerable depth along trends perpendicular and parallel to the mountain front. In fact, here the highest-yielding fractured Paskapoo sandstone aquifers typically occur in proximity to the drift-bedrock contact at depths of 20-30 m, in zones parallelling the Rockies (Vogwill, 1983). He suggested that groundwater flow in the Paskapoo consists of a series of rapidly-moving, local and intermediate flow systems in well-fractured sandstone collector units, superimposed on a larger regional system which discharges to the northeast (Vogwill, 1983).

Parks and Tóth (1995) studied the hydrogeological aspects of the post-Colorado second-order sequence in an area southwest of Edmonton, subdividing the stratigraphy into regional aquifers (Belly River Group), regional aquitards (Lea Park and Bearpaw formations), and strata of mixed properties (Edmonton Group, Scollard Formation and Paskapoo Formation). These strata lie beneath a veneer of glacial till to a depth of 1500 m in the area and, as in most areas of western Alberta, most local water wells are completed in strata of the Paskapoo Formation (Parks and Tóth, 1995). Here, Paskapoo formation pressures are near-hydrostatic or just sub-hydrostatic (likely due to Quaternary removal of significant thicknesses of overburden) and wells yield groundwater with 500-1000 mg/L total dissolved solids (ie. possibly useful for irrigation and watering livestock, but likely beyond the range for municipal use) (Lennox, 1993; Parks and Tóth, 1995).

Summary

The third-order Paskapoo-Porcupine Hills sequence contains significant hydrogeological resources which are currently being exploited for agricultural, municipal and industrial uses. To date, much of the water production has been acquired through serendipitous drilling, rather than concerted scientific exploration. Further potential certainly exists but is currently not predictable, and aquifers must be protected from over-development and contamination. Much more, careful research is required to properly evaluate the groundwater resources of these strata for the benefit of all.

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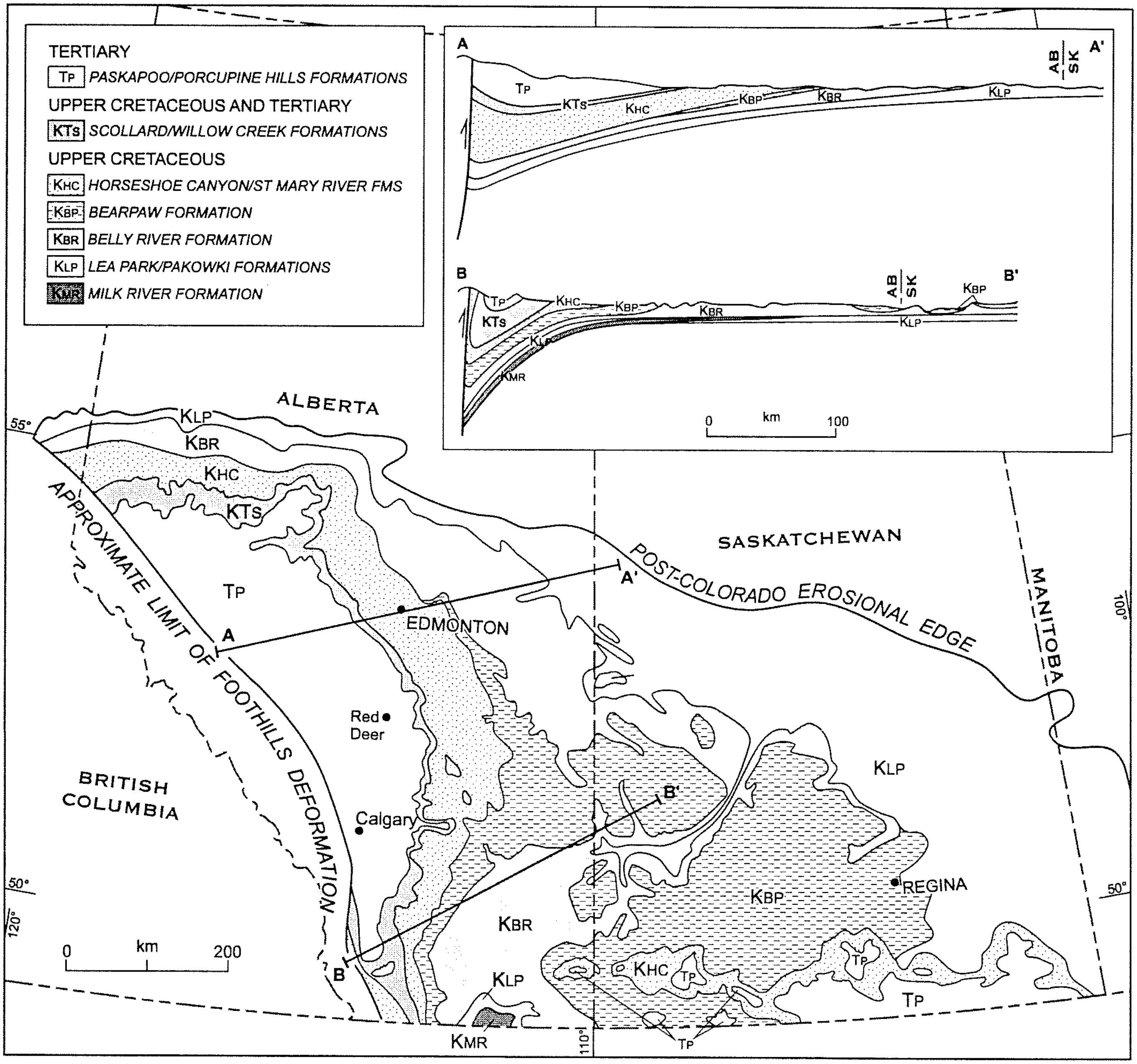

Figure 1. Upper Cretaceous-Tertiary depositional assemblages (clastic wedges), Western Canada Sedimentary basin.

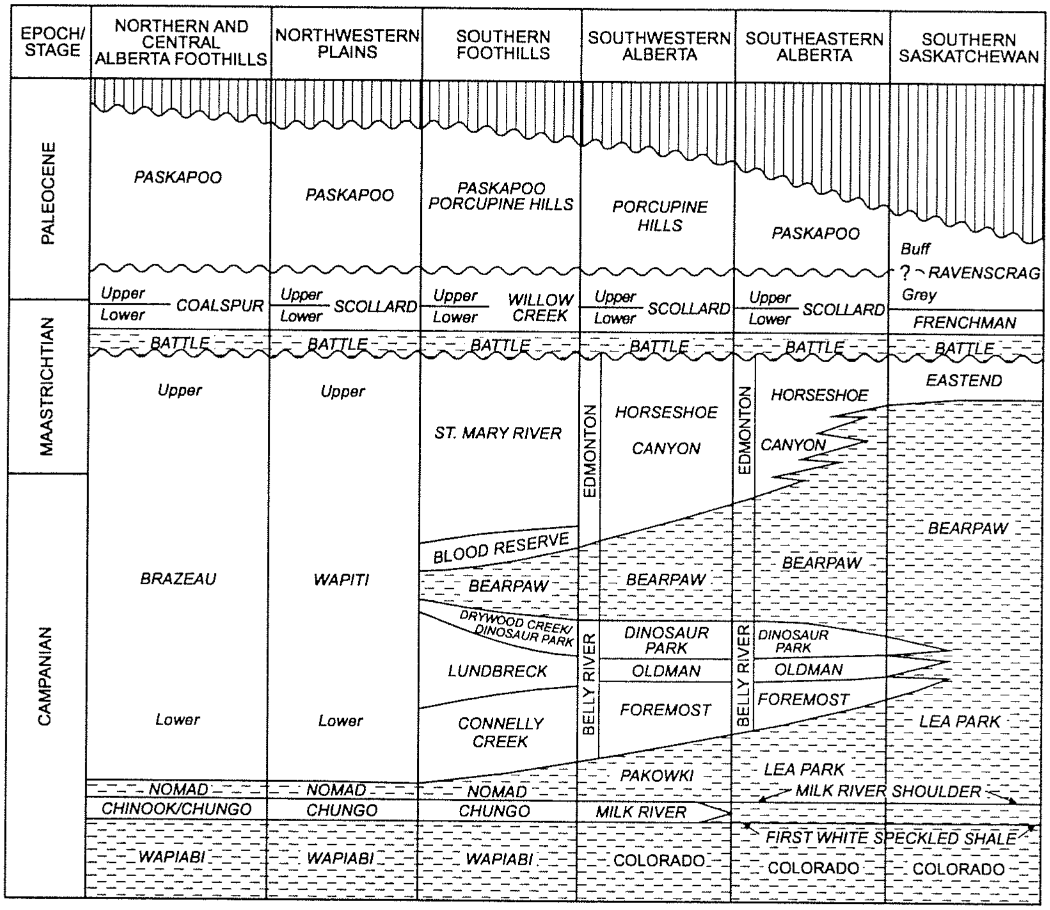

Figure 2. Upper Cretaceous-Tertiary stratigraphic columns.