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Scollard/Willow Creek/Coalspur formations: summary of literature and concepts

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Abstract

This Open File represents a brief summary of information, gleaned from published literature, on the geology of the Scollard, Willow Creek and Coalspur formations (and equivalents), of Upper Cretaceous-Tertiary age. This compendium, and the enclosed references, can provide a background to further research on these strata, which have both scientific and economic interest. These clastic, generally non-marine rocks are well-exposed in certain localized parts of Alberta and Saskatchewan, include the famed K-T boundary, and also harbour significant potential for shallow gas, coal-bed methane, uranium, and groundwater resources.

General Tectonic and Depositional Setting

Foreland Basin Basics

In the Western Canada Sedimentary Basin (WCSB) the Foreland Basin Succession is the second of two major eastward-thinning wedges, is approximately equivalent to the Zuni Sequence of Sloss (1963), and is a direct result of the evolution of the Canadian Cordillera during Jurassic to Paleocene time (Porter et al., 1982). 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). 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 in that foredeep. 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).

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 km 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), led to rapidly intensifying tectonic loading, foredeep subsidence (creating accommodation space) and cannibalization of previous deposits. This resulted in Campanian to Paleocene rapid deposition of a series of generally regressive wedges of marine to nonmarine synorogenic molassic sediments (Jerzykiewicz, 1985). This composite coarsening-upward succession, up to 3.5 km thick, was deposited over a period of 20-25 m.y. (sedimentation rate of about 175m/m.y.) and represents the final stage of Foreland evolution (Porter et al., 1982).

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 wedges. Jerzykiewicz and Labonte (1991) and Leckie and Smith (1993) noted that prevailing drainage in the proximal part of the post-Colorado foreland is perpendicular to basin axis in more proximal, coarser-grained phases and parallel to basin axis in more distal, finer-grained phases.

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) but was later partially eroded after thrusting ceased and crustal extension began in Eocene time (Monger, 1989), leaving only erosional remnants over the Plains. 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).

Hamblin (2004) described the tectonic, stratigraphic and depositional setting of the second-order Upper Cretaceous-Tertiary succession in the Western Canada Sedimentary Basin. He suggested that the Scollard/Willow Creek/Coalspur (and equivalents) represents the fourth of five third-order successions, and is separated from those above and below by regional unconformities (Fig. 1). Similarly, six coarsening-upward cyclothems, related to orogenic pulses, were identified by Jerzykiewicz (1985) in this succession in the central Foothills : the Scollard/Willow Creek/Coalspur strata correlate to his Cycle V. 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. Campanian subsidence and sedimentation rate increased markedly in southwestern Alberta, but decreased northward, whereas in the Maastrichtian, these rates increased markedly in northwestern Alberta and decreased progressively southward (Chamberlain et al., 1989). 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 Scollard/Willow Creek/Coalspur Clastic Wedge

The Scollard/Willow Creek/Coalspur succession occurs near the top of an overall coarsening-upward regional succession representing infill of the foreland basin controlled by tectonic processes (Jerzykiewicz, 1985; Mack and Jerzykiewicz, 1989). It represents part of this vast eastward-thinning wedge of generally fluvial sediments which extended from the late Cretaceous/early Paleocene deformational front to Manitoba (Taylor et al., 1964; Gibson, 1977). Jerzykiewicz (1997) refers to this as his third-order Sequence I. Deposition occurred along the western margin of a subsiding, confined marine seaway (connected to the Arctic? or the Gulf?) as indicated by the presence of the equivalent Cannonball Member in Montana, North Dakota and Manitoba (Taylor et al., 1964; Rahmani and Lerbekmo, 1975; Gibson, 1977). Thus, much of the preserved sediments were deposited up to 800 km inland from shore (Richardson et al., 1988). According to Jerzykiewicz (1985) and Mack and Jerzykiewicz (1989) coarser clastic deposition was initiated by a thrust phase at about 66 Ma and continued through a phase of tectonic quiescence with finer grained deposits and coals, followed by reactivation of thrusting to start Paskapoo deposition. 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 greater thickness of Scollard-age sediments, and greater thickness and number of coals to the west (Richardson et al., 1988). In addition, there was a period of intense volcanism to the west immediately preceding and during deposition (Elliot, 1960; Gibson, 1977; Sweet, 1990). The lower part of the clastic wedge is dominated by coarser clastics and sedimentary rock fragments suggesting that thrusted Paleozoic and Mesozoic rocks supplied the detritus, whereas the upper part is dominated by finer grained sediments with an increase in metamorphic rock fragments, suggesting that thrust plates may have been partially eroded and that some detritus from the

Omineca area of central British Columbia was re-incorporated into the dispersal pattern (Mack and Jerzykiewicz, 1989).

The base and top of the Scollard/Willow Creek wedge may be disconformable (Dawson, 1990; Glass, 1990) and there has been considerable discussion of the relationship to over- and under-lying units (Douglas, 1950; see Jerzykiewicz, 1997; see Hamblin, 2004, for further details). In general, it appears that the base is sharp and marked by the Entrance Conglomerate in the central Foothills and by some erosional bevelling to the east (Irish, 1970; Furnival, 1950; Lerbekmo, 1987; Braman, 1990; Jerzykiewicz, 1997). However, in the southern Foothills, Douglas (1950) implied that the contact between the St. Mary River Formation and the Willow Creek Formation is conformable and transitional. The upper contact with the Paskapoo is marked by the High Divide Ridge Conglomerate in the central Foothills and some erosional bevelling to the east (Ower, 1960; Elliot, 1960; Allan and Sanderson, 1945; Jerzykiewicz, 1997), and by a conglomeratic sandstone and erosional bevelling in the southern Foothills (Douglas, 1950; Tozer, 1956).

Stratigraphic Setting and Boundaries (Fig. 2)

Foothills

In the central Foothills, the Coalspur Formation is approximately equivalent to the Scollard in the Plains. At the base of the Coalspur is the Entrance Conglomerate (Lang, 1946) which abruptly (unconformably?) overlies the upper Brazeau Formation which contains a Battle-like shale with a tuff, like the Kneehills Tuff of the Plains (Jerzykiewicz and McLean, 1980). It is overlain by the rest of the Coalspur Formation (as used by MacKay, 1949, Jerzykiewicz and McLean, 1980 and Jerzykiewicz, 1985). As mentioned by Dawson (1990) the Entrance-Coalspur may have disconformities at both base and top. The Cretaceous-Tertiary boundary has been located within the Coalspur, at the base of the Mynheer coal seam (Jerzykiewicz, 1985). In the southern Foothills Russell and Landes (1940) and Douglas (1950) noted that the Willow Creek has a generally sharp but likely conformable, base on the underlying St. Mary River Formation, although on the east side of the Alberta Syncline there may have been erosion at that contact (Glass, 1990). The Willow Creek, unlike coeval strata elsewhere in the basin, is virtually devoid of coal (Jerzykiewicz and Norris, 1992). The upper contact is gradational and conformable.

Plains

In the Plains the Scollard has been studied for many years, although generally included as part of the Edmonton Group. It is well exposed in the Red Deer River valley from Twp 32-40 (Gibson, 1977). Allan and Sanderson (1945) suggested that the base of their Upper Edmonton (ie. Scollard Formation) should be the top of the Kneehills Tuff Zone and the top should be the disconformity at the base of the Paskapoo. Ower (1960) provided the first major study of the Edmonton Group and referred to his Member E, or Upper Edmonton of Lance age, above the Kneehills Tuff Zone and conformably beneath the Paskapoo. He detected no major pre-Paskapoo erosion in the Red Deer River Valley, but suggested there may be progressive west-to-east regional scale bevelling below the Paskapoo. Elliot (1960) also used Ower's Member E in the subsurface but included a very perceptive conceptual idea: He realized that the Member E/Paskapoo contact was more difficult to pick toward the west because either, a) there was a major disconformity at the base of the Paskapoo which cuts downward through stratigraphy to the east, or b) there was more rapid and continuous subsidence to the west, allowing deposition and preservation of younger uppermost Edmonton strata before Paskapoo deposition. Campbell (1962; 1967) also used Ower's Member E terminology to include all strata above the Kneehills Tuff Zone and below the thick Paskapoo sandstone as part of the Upper Edmonton, but failed to observe the Edmonton/Paskapoo disconformity suggested by Allan and Sanderson (1945). Srivastrava (1968) included these rocks in the upper Edmonton, but recognized a lower sandstone-dominated portion referred to as the "mammal-bearing member" and an upper coaly portion formally-defined as the Nevis Member. It is now known that the Cretaceous-Tertiary boundary occurs at the contact of these two units.

Irish (1970) produced a major study of the Edmonton Group, reviewed all previous stratigraphic terminology and suggested that Ower's Member E or Upper Edmonton was more like the overlying strata and hence established the new Scollard Member as a unit at the base of the Paskapoo. He defined a type section in Scollard Canyon. He viewed the Battle-Kneehills Tuff Zone as the only useful marker in that part of the section, echoing the paleontological observations of Sternberg (1947) and Srivastrava (1968), and defined it as the upper unit of the Edmonton Group. He noted that the Battle Formation was removed by pre-Scollard (channel?) erosion in Twp 10-22 in the outcrop belt suggesting the major depositional break and disconformity should be placed at that position. Gibson (1977) reviewed the earlier terminology confusion and suggested that the basal contact with the Battle is conformable but the upper contact, placed at the base of the consistent massive sandstone, has some local channel erosion, although it is likely not disconformable. Gibson (1977) altered the Irish (1970) nomenclature to include the distinctive Scollard unit as a Formation of the underlying Edmonton Group, and suggested new type sections which illustrate the entire member (located at SE 3-34-22W4 and E 7-11-34-22W4 on the west side of the Red Deer River valley). The Battle/Scollard contact is certainly sharp and is erosional in T 22-26, whereas the Scollard/Paskapoo contact is sharp, very variable and involves channel erosion (Dawson, 1990; Glass, 1990).

Hamblin (2004) provided an extensive summary of recent paleontological and magnetostratigraphic work related to the underlying Horseshoe Canyon Formation, and it's contact with the Scollard. Catuneanu and Sweet (1999) confirmed that there is a disconformity of significant duration between the upper Horseshoe Canyon and the overlying Battle Formation or Scollard Formation, whereas Lerbekmo and Coulter (1985) stated that the upper contact of the Battle with the Scollard is conformable. Clearly, the base of the Scollard/Coalspur is disconformable.

Cypress Hills

In the Cypress Hills area the Frenchman Formation, originally called Division B of the Lignite Tertiary by Dawson (1875), has a regional basal unconformity, correlated to the base of the Scollard and base of the Entrance Conglomerate (Braman, 1990). McLearn (1928) first recognized this widespread erosion, with up to 60 m of topography, which cuts down eastward to the Whitemud Formation, and even down into the Bearpaw in some places (Furnival, 1950). It is similar to the unconformity at the base of the Hell Creek Formation in Montana (Furnival, 1950). The Frenchman is late Maastrichtian in age and correlates to the lower Scollard, whereas in southwestern Saskatchewan the "grey facies" of the Ravenscrag Formation (Furnival, 1950), 38 m of grey shale, lignite and minor sandstone, is now considered as earliest Paleocene in age and equivalent to the upper Scollard (Sweet, *pers. comm.*). The overlying "buff facies" of the

Ravenscrag (Furnival, 1950) is approximately equivalent to the Paskapoo Formation (Sweet, *pers. comm.*).

Cretaceous-Tertiary Boundary

The highest dinosaur beds in the Red Deer River valley are now known to be 2.3 m below the Nevis coal seam, contrary to mistaken levels recorded by earlier workers, and the Cretaceous/Tertiary (K/T) boundary can be placed through palynological study at the base of the Nevis seam in central Alberta, and the base of the Ferris seam in Saskatchewan (Sweet, 1990). Tozer (1956) demonstrated the presence of Cretaceous faunas in the lower Willow Creek, but Paleocene faunas in the upper Willow Creek of the southern Foothills. The important coal-bearing strata were deposited immediately after the K/T boundary and, in addition correlate to the marine transgression of the Cannonball Member in Manitoba (Sweet, 1990; Sweet, *pers.comm.*). Palaeomagnetic work by Lerbekmo (1985, 1987) has shown that the sub-Frenchman disconformity in Cypress Hills includes about 0.3 to 2 Ma of time and is represented in central Alberta by 50-60 m of Horseshoe Canyon strata. This confirms that the Battle Formation is a diachronous facies, slightly younger in central Alberta than in Saskatchewan.

Age and Correlation (Fig. 2)

The Scollard/Willow Creek/Coalspur/Frenchman-Ravenscrag clastic wedge is unique in that it is now known to enclose the Cretaceous/Tertiary (K/T) boundary (Fig. 2). In fact, the K/T boundary separates the lower and upper members of this unit (Braman and Sweet, 1990). Hence, the lower non-coaly portion of the Scollard in central Alberta is late Maastrichtian (Lancian) in age and the upper coaly part is earliest Paleocene (P1/P2) age, with the boundary placed at the base of the Nevis seam (Richardson et al., 1988). In North Dakota and Manitoba the K/T boundary is placed at the base of the Cannonball (marine shale) Member of the Fort Union Formation (Russell and Singh, 1978; Sweet, 1990, *pers.comm.*). The highest dinosaur bones are now known to occur in the Red Deer River valley up to a point only 2.3 m below the Nevis seam (Sweet, 1990). In addition, radiometric dating places the Kneehills Tuff Zone, immediately underlying the Scollard, at 66 Ma and the Ardley seam in the upper part of the Scollard at 63 Ma (Srivastrava, 1970), confirming that the unit encompasses about 3-4 Ma of deposition spanning the K/T boundary (65 Ma). Recent palaeomagnetic work in central and southern Alberta has illustrated that the K/T boundary occurs 3 m below the top of polarity chron zone 29r in both areas (Lerbekmo, 1985) and thus can be considered essentially a time line.

In the central Foothills the Entrance Conglomerate occurs at the base of the Coalspur, just above the Kneehills Tuff Zone and thus represents the base of the upper Edmonton Member E of Ower (1960). The Coalspur is correlated to part of the Wapiti, the Scollard, the Willow Creek and part of the Ravenscrag (Glass, 1990). In the southern Foothills, members A, B, C and most of D of the Willow Creek (Douglas, 1950) are correlated to the lower Scollard, the Frenchman and the Lance and Hell Creek formations in the U.S. (Tozer, 1956; Campbell, 1967). In the Alberta Plains the Scollard Formation is correlated to the upper Wapiti of the northern Plains, the Coalspur of the central Foothills, the Willow Creek of the southern Foothills, the Frenchman and Ravenscrag of the Cypress Hills (Glass, 1990), the Hell Creek, Lance and lower Fort Union of Montana and Wyoming (Irish, 1970).

In the Cypress Hills area of southern Alberta and Saskatchewan the Frenchman Formation is correlated to the upper Brazeau of the central Foothills, the Willow Creek of the southern Foothills and the Hell Creek of Montana (Glass, 1990). The basal unconformity of the Frenchman is equated to that of the Entrance Conglomerate in the central Foothills (Braman, 1990). The Cannonball Member marine tongue of the Fort Union Formation in Montana, North Dakota and Manitoba is approximately equivalent to the Ardley Coal Zone in the Paleocene portion of the Scollard (Sweet, 1990, *pers.comm.*).

Thickness

In the central Foothills the basal Entrance Conglomerate is up to 30 m but generally <10 m thick, whereas the overlying Coalspur, or Unit 5, is 300-450 m or even 550 m in estimated thickness (Jerzykiewicz and McLean, 1980; Glass, 1990). In general, the Scollard clastic wedge, and its component parts, thicken to the west beneath the overlying Paskapoo, away from the outcrop belt, from 85 m in outcrop to >400 m in the subsurface to the west (Ower, 1960; Elliot, 1960; Richardson et al., 1988). In outcrop along the Red Deer River it is about 85-88 m (Allan and Sanderson, 1945; Gibson, 1977) although Irish (1970) suggested the thickness was very variable due to erosion. In fact, Ower (1960) measured only 56 m of his Member E (Scollard-equivalent) in the Scollard Canyon area. Gibson (1977) measured the lower barren zone (lower Scollard) as 35-45 m. Most authors have also observed that the Scollard thickens from north to south as well as from east to west: 107 m at Three Hills/122 m at Battle Lake (Ower, 1960), up to 110 m along the outcrop belt of Red Deer River (Campbell, 1967). In the southern Foothills the Willow Creek is estimated to be 1000-1300 m thick (Douglas, 1950; Tozer, 1956). In the Cypress Hills, the Frenchman Formation (lower Scollard-equivalent) has thicknesses of 60-113 m and thins to the east (Furnival, 1950; Braman, 1990; Glass, 1990).

Coal Zones

The bulk of the economic coal in the Early Paleocene of the Alberta basin occurs in the Scollard Formation of central Alberta, although the Coalspur of the central Foothills has some important reserves too. In the central Foothills the Coalspur Formation has seams in its upper part, or Saunders Vb (Jerzykiewicz, 1985), in an interval about 270-400 m above the base (Glass, 1990). These seams range over 60-180 m of stratigraphy and may correlate to the Ardley seams of the Scollard Formation (Jerzykiewicz and McLean, 1980). In that area there is a rapid decrease in thickness and number of seams toward the southwest, ie. toward the sediment source (Jerzykiewicz and McLean, 1980).

The naming of coal seams has led to some confusion in Scollard stratigraphy through the years. In his Member E of the Red Deer River valley Ower (1960) defined and correlated several seams. He suggested that 1) the Ardley seam, 8-10 m thick and 27 m above the base, was correlative with seam 39 m above the base at Trochu and the "Big Seam" 15 m above the base at Wabamun Lake, and that 2) the Upper Ardley seam, 2-3 m thick, was 61 m above the base at Trochu and 55 m above the base at Lacombe. Campbell (1967) noted that a) the Ardley Coal Zone was first noted by Tyrrell (1887) who made it the upper boundary of the Edmonton; b) that it is the first coal above the Kneehills Tuff Zone; and c) it is in the middle of the Scollard. He viewed it as very consistent in thickness and occurrence, from Red Deer River (T 29 R 17W4) to Grande Prairie (T 64 R 11W6) and also in Cypress Hills and therefore likely isochronous. Campbell (1967) described the Zone as 7-24 m thick with four parts, in ascending order a) lower seam 0-1m thick, b) grey and green carbonaceous shale with lenses of coal and bonebeds, c) upper seam 1-2 m thick with a thin bentonite bed, d) coaly shale. Irish (1970), in his work on the

Edmonton Group, observed the main coal seam but missed the upper one because his type section ended at the Ardley Zone, a problem addressed by Gibson (1977).

Gibson (1977) described the coaly upper member of the Scollard (Nevis Member of Srivastrava, 1968) as being about 40-50 m of the total 85 m thickness, with coals enclosed by finer grained sediments, and with two main coal zones. The lowermost zone, the "Nevis", or "lower Ardley A", or "#13" seam (Ardley seam of Ower, 1960) is 36-46 m above the base, is up to 3 m thick, consisting of interbedded brown coaly shale, bentonite and coal seams up to 1.4 m thick, and is very distinctive. It thickens to the north and is closer to the Scollard base to the north (Gibson, 1977; Glass, 1990). The base of the Nevis Seam marks the stratigraphic position of the Cretaceous-Tertiary boundary (Richardson et al., 1988). The upper zone, the "Ardley", or "lower Ardley B", or "#14", or "Big Seam", or "Pembina Seam" (upper Ardley seam of Ower, 1960) is 15-18 m above the Nevis (ie. 57-65 m above the Scollard base), is up to 3.5 m thick, consisting of interbedded coaly shale, bentonite and coal seams up to 1.8 m thick, and is the main economic zone. It lies closer to the Scollard base to the north and is up to 7 m thick in the subsurface at Red Deer, and up to 13 m thick at Wabamun Lake (Glass, 1990). There are several thin shaley coals 15-46 m above this Ardley Seam, commonly called the Upper Ardley seams (Gibson, 1977). In the Cypress Hills area there is minor coal and lignite above the K/T boundary (Glass, 1990).

The Ardley Coal Zone occurs from about Twp 30-64 and from outcrop to the disturbed belt, encased in nonmarine fluvial, lacustrine and paleosol sediments (Richardson et al., 1988), although it is approximately equivalent to the marine Cannonball Member of Manitoba and North Dakota (Sweet, *pers.comm.*). The presence of thick, extensive coal seams, correlatable over several Townships requires originally very large peat mires which, likewise, required rapid subsidence and shelter from coarse clastic input over large areas (Richardson et al., 1988). Toward the west the Scollard thickens, the Ardley Coal Zone thickens from 14 to 200 m, and the thickness and number of individual seams increases; all clear evidence that there was greater subsidence to the west during deposition of the Scollard, as would be expected in a foreland basin during an active phase (Richardson et al., 1988). In addition, Richardson et al. (1988) noted that Scollard coals are thickest in an east-west trend in Twp 47-48 Rge 1-17W5 and a north-south trend in Twp 47-59 Rge 20W5.

Climate

Deposition of the Scollard occurred at a paleolatitude of about 60^{o} N but the late Maastrichtian climate was warmer than the present-day climate at that latitude (Richardson et al., 1988). There was a moderate trend toward cooler and more arid conditions toward the end of the Cretaceous and beginning of the Paleocene (Srivastrava, 1970; Russell and Singh, 1978). Lerbekmo (1985) suggested the Battle/Whitemud, the stratigraphic unit immediately beneath the Scollard, represents unusual climatic/topographic conditions and is a diachronous facies, younging from east to west. The presence of thick coals suggests that basinwide climatic and tectonic subsidence factors were of paramount importance in understanding Scollard/Coalspur deposition (Richardson et al., 1988).

The most comprehensive study of climatic evidence and influences in this part of the stratigraphic section is that of Jerzykiewicz and Sweet (1988) and is summarized here. Three different floodplain facies occur: 1) dark, organic-rich, coal-bearing mudstone in the Paleocene portion of the Scollard and Coalspur, representing persistent humid conditions, which is conspicuous north of Twp 30 (Richardson et al., 1988); 2) vari-coloured mudstone with mature caliche glaebules and hardpan in the Willow Creek of the southern Foothills, representing persistent semi-arid conditions; and 3) greenish grey mudstone of the Frenchman and Maastrichtian portion of the Scollard and Coalspur, representing an intermediate association deposited in a low-sinuosity meandering fluvial system. Caliche and hardpan development requires long periods of non-deposition and exposure (1000's to 100,000's of years) coupled with a warm, semi-arid climate with alternations between drought (carbonate precipitation) and rain (carbonate dissolution) (Jerzykiewicz and Norris, 1992). This facies is persistent in the southern Foothills and adjacent Plains, is less persistent to the north (Russell and Landes, 1940), and correlates to the late Maastrichtian peak of regression and coarse clastic influx. Jerzykiewicz and Sweet (1988) suggested a dominant topographic/tectonic control which resulted in climatic partitioning of the basin. Thick coals require the persistence of moderate to high precipitation over most of the year with attendant intense chemical weathering. The most widespread coaly period was immediately after the K/T boundary, even in the semi-arid area to the south, where caliche and red beds decrease upward and fossiliferous mudstone increases upward. During that time the coal-bearing facies expanded south and west to overcome much of the semi-arid area. Sweet (1990) also noted that the K/T boundary marks the start of the coal-bearing sequence after a barren sequence, likely as a result of a regional rise in the water table and climatic change.

From a detailed study of petrography, paleontology and mineralogy, Potter et al. (1991) concluded that Ravenscrag deposition in southern Saskatchewan occurred in humid, warm-temperate to subtropical conditions. Peats accumulated subaquatically with a diverse flora of cypress and fern forests characteristic of low moor freshwater swamps with periodic exposure and desiccation (Potter et al., 1991).

Paleontology

A major floral and faunal break occurs at the base of the Scollard in Red Deer River valley between the top of the typical Maastrichtian assemblage and the distinct Lancian assemblage of the Scollard (Sternberg, 1947; Srivastrava, 1968). The paleontology of the Scollard is important and interesting because of the unique occurrence of the K/T boundary in the middle of the formation. Early reports on the Scollard mentioned a Lance, or *Triceratops* fauna with very few Hadrosaurs, especially in the lower part (Sternberg, 1947; Ower, 1960; Elliot, 1960). Sternberg (1947), Campbell (1967) and Irish (1970) listed a typical Lance dinosaur fauna of *Triceratops*/*Tyrannosaurus*/*Ankylosaurus*. This is in direct contrast to the Hadrosaur-dominated fauna of the underlying Edmonton (Sternberg, 1947). Gibson (1977) noted that there were few fossils, except minor pelecypods and gastropods, plus the dinosaurs and mammals. Ceratopsian dinosaurs were also noted in the Frenchman Formation (Furnival, 1950; Glass, 1990) and suggested correlation to the Scollard. The rich fossil flora of the Ravenscrag Formation of southwestern Saskatchewan provides a window on the depositional setting and paleoclimate of the early Paleocene (McIver and Basinger, 1993). The Willow Creek is generally barren but yields a few freshwater fish, molluscs, and turtles from the upper member (Russell and Landes, 1940; Braman and Sweet, 1990) and a few dinosaur bones from the lower member, including a major discovery of a near-complete *Tyrannosaurus rex* skeleton near Cowley (Braman and Sweet, 1990). Tozer (1956) pointed out the presence of the K-T boundary within the Willow Creek. In addition, mammalian fossils are known from the lower Scollard (Srivastrava, 1968).

The most important recent work has described the exact position of the K/T boundary, where the diverse, angiosperm-rich and dinosaur-bearing late Maastrichtian assemblages of the lower Scollard were replaced by the impoverished, low-diversity, gymnosperm-rich and non-dinosaur-bearing earliest Paleocene assemblages of the upper Scollard (Richardson et al., 1988; Jerzykiewicz and Sweet, 1988). This apparently abrupt change occurs at the base of the Nevis seam (ie. base of coal-bearing upper Scollard) in central Alberta, at the base of the Ferris seam in Saskatchewan (Richardson et al., 1988; Jerzykiewicz and Sweet, 1988; Sweet, 1990), and at the base of the Mynheer seam in the central Foothills (Jerzykiewicz, 1985) (Fig. 2). However, Sweet et al. (1990) described data suggesting that changes in the palynoflora may have been related to variations in depositional environments and paleolatitude rather than a single catastrophic event. This clastic wedge thus holds a unique position in the stratigraphy of the basin.

Magnetostratigraphy

Magnetostratigraphic studies on the strata above and below the K/T boundary in WCSB have elucidated details of depositional events of this crucial time period. The Cretaceous-Tertiary boundary in western North America is now established as occurring within the 29r magnetozone (Lerbekmo and Coulter, 1985; Lerbekmo et al., 1996; Swisher et al., 1993), as is the case elsewhere in the world. This occurs in the middle of the Scollard/Willow Creek/Coalspur succession, almost always associated with a thin coal seam. However, detailed study by Lerbekmo et al. (1996) suggested that a brief normal polarity subchron may mark the actual boundary in sections where sedimentary continuity is preserved. Lerbekmo et al. (1995) discerned a major sub-Paskapoo disconformity at the top of the Scollard, which encompasses magnetozones 27r, 28 and part of 28r, representing a substantial time gap. Clearly, the depositional record of these rocks is complex and would benefit from further study.

Sedimentology

Foothills

In the Central Foothills the Entrance Conglomerate is massive framework-supported conglomerate with a coarse sandstone matrix, to interbedded conglomerate and coarse sandstone (Jerzykiewicz, 1997) overlain by thick interbedded channel sandstone/splay sandstone/overbank fines, referred to as Cycle Va by Jerzykiewicz (1985). Clasts are up to 20 cm but generally 1-5 cm, rounded, well sorted with good imbrication (Jerzykiewicz and McLean, 1980; Jerzykiewicz, 1997). Massive to crudely horizontal bedding is characteristic, sandstone beds have planar-tabular crossbeds, paleoflow directions were to the northeast and deposition occurred as longitudinal bars in fluvial channels (Jerzykiewicz and McLean, 1980). The ratio of thick channel sediments and thin splay sandstones vs. overbank fines is 56% or about 1:1 (Jerzykiewicz, 1985). The overlying Coalspur (Cycle Vb of Jerzykeiwicz, 1985) generally comprises massive to thinly interbedded sandstone, siltstone, mudstone and coal with minor conglomerate, bentonite and tuff deposited in a fluvial setting (Jerzykiewicz, 1985). The lower part is barren of coal and characterized by thick fine to very coarse, sharp-based sandstone and thinly interbedded greenish mudstone/siltstone/fine sandstone deposited in a low sinuosity meander belt (Jerzykiewicz and McLean, 1980; Jerzykiewicz and Sweet, 1988). The K/T boundary occurs at the base of the Mynheer coal seam and the upper part consists of laterally persistent coals, overbank mudstone and siltstone, common bentonites and thin splay sandstones (rare thick channel sandstones) deposited on a humid floodplain (Jerzykiewicz, 1985;

Jerzykiewicz and Sweet, 1988). The ratio of sandstone to siltstone is about 67% or about 1:2 (Jerzykiewicz, 1985).

In the southern Foothills the Willow Creek Formation is predominantly alternating vari-coloured claystone and lesser soft grey calcareous sandstone, characterized by brilliant colour banding which fades to the north (Russell and Landes, 1940; Hage, 1943; Douglas, 1950; Tozer, 1956; Jerzykiewicz and Norris, 1992; Jerzykiewicz, 1997). Irregular, calcareous concretions are abundant within the reddish shales and the strata are generally poorly-fossiliferous (Hage, 1943). Douglas (1950) described five zones, in ascending order a) 163 m green and purple shale with fine sandstone b) 75 m green and red shale and sandstone c) 10 m grey coarse sandstone to conglomerate with crossbedding, d) coloured shale with minor sandstone, e) thick coarse sandstone beds (d&e=580 m). Both mudstones and sandstones typically contain redeposited caliche nodules (Jerzykiewicz and Norris, 1992). The Willow Creek is now generally divided into a lower part of calcareous red beds and caliche/hardpan zones deposited on a semi-arid floodplain, and an upper part with thick trough crossbedded sandstone, dark grey fossiliferous mudstone and minor caliche beds (Jerzykiewicz and Sweet, 1988; Braman and Sweet, 1990). The K/T boundary lies at the contact between these two (i.e. somewhere within Douglas' zone d).

Plains

In the Plains of central Alberta the Scollard Formation is mostly interbedded, light coloured fine-grained, argillaceous sandstone, siltstone and mudstone with thick, widespread coal seams in the upper half, and scattered bentonite beds (Allan and Sanderson, 1945; Glass, 1990). Sandstones are light grey to buff weathering, very fine to medium grained, quartzose, bentonitic, locally very calcareous and generally in lenticular beds up to 1.5 m thick with small to medium scale trough crossbedding and planar tabular crossbedding (Irish, 1970; Gibson, 1977). The basal sandstone may be up to 8.5 m thick, of medium to coarse grain size, and cuts down into the underlying Battle and Whitemud Formations (Ower, 1960; Irish, 1970; Gibson, 1977). These basal sandstones are excellent aquifers (Sternberg, 1947). Interbedded fine sediments are alternations of a) greenish, bentonitic sandy or silty mudstone/siltstone, and b) dark grey to purple, very bentonitic, silty to sandy mudstone (Battle-like in appearance) with coal seams (Irish, 1970; Gibson, 1977). The lower Scollard (Maastrichtian age) is about 40-45m thick in outcrop, and is dominated by thick sandstone with greenish grey shale and thin sandstones (Fig. 3) deposited in a low sinuosity meander belt (Jerzykiewicz and Sweet, 1988). This is the unit Srivastrava (1968) referred to as the "mammal-bearing member". The upper Scollard (Paleocene age) is about 40-50 m thick in outcrop, and is dominated by dark grey, bentonitic mudstone with coals (Ower, 1960; Gibson, 1977) (Fig. 2) deposited in a humid floodplain (Jerzykiewicz and Sweet, 1988). Srivastrava (1968) formally defined these strata as the Nevis Member. According .

to Richardson et al. (1988), Scollard rivers were likely shallow and sluggish, and there were extensive peat mires where there was little or no clastic input for long periods. Eberth and O’Connell (1995) discerned a transition from low sinuosity channel forms to higher sinuosity channel forms across the K/T boundary within the Scollard Formation, interpreted to represent a change to a wetter climate. The coal zones of the upper Scollard/Coalspur are tentatively correlated to the earliest Paleocene marine transgression recorded by the Cannonball Member in Manitoba (Sweet, 1990), a hypothesis rejected by Eberth and O’Connell (1995).

Cypress Hills

In the Cypress Hills area the Frenchman Formation was first described in detail by Furnival (1950) as medium to coarse sandstone with minor siltstone, shale and lignite, although Braman (1990) noted that in some outcrops it comprises mostly light greenish or brownish bentonitic claystone. Sandstones are greenish to brownish, range from fine to coarse grained (generally medium to coarse grained), hard, crossbedded, well sorted and feldspathic (Furnival, 1950). They occur in sharp-based fining-upward units with shale rip-ups and quartzite pebbles at the base, with calcareous concretions and thin shale laminae and thinly interbedded siltstone to very fine sandstone beds near the top (Furnival, 1950; Braman, 1990). Deposition is interpreted to have occurred on a low sinuosity meander belt in a semi-humid climatic setting (Jerzykiewicz and Sweet, 1988).

Petrography

In the central Foothills the Entrance Conglomerate has clasts up to 15 cm, but generally 1-5 cm in diameter, which are well rounded, well sorted and imbricate (Jerzykiewicz and McLean, 1980). They are typically of quartzite or chert composition plus some pelitic sedimentary rock fragments and some volcanic/metamorphic detritus (Jerzykiewicz and McLean, 1980). The Entrance represents Petrographic Stage III of Mack and Jerzykiewicz (1989) in which there was a decrease in metamorphic detritus, and an increase in sedimentary detritus, suggesting renewed thrusting and dominance of thrust-belt Phanerozoic sedimentary rocks in the sediment source area. In the southern Foothills the lower Willow Creek is also part of Petrographic Stage III in which metamorphic rock fragments decrease and sedimentary rock fragments (especially chert and carbonates) increase, with a slight decrease in volcanic detritus Mack and Jerzykiewicz, 1989). These authors also pointed out a distinct increase in coarser sandstone in thicker channels and abundant red beds/caliche. This Stage III suggests that a major thrusting phase correlated approximately with the Kneehills Tuff Zone, immediately preceding Coalspur/Willow Creek deposition at about 66 Ma (Mack and Jerzykiewicz, 1989) and led to this deposition.

The bulk of the Coalspur in the central Foothills and the upper Willow Creek in the southern Foothills are characterized by an increase in metamorphic (with consistent sedimentary) rock fragments and are designated Petrographic Stage IV by Mack and Jerzykiewicz (1989). Summarizing data from these authors indicates that the composition of framework grains in the Willow Creek is about 45% quartz (mostly sedimentary mono-quartz), 7% feldspar (mostly volcanic plagioclase), and 48% rock fragments (mostly chert sedimentary fragments with some volcanic and metamorphic detritus). Likewise, for the Coalspur, 26% quartz (mostly sedimentary mono-quartz), 20% feldspar (virtually all volcanic plagioclase), and 54% rock fragments (mostly volcanic and metamorphic detritus).

In the Plains, sandstones in the Scollard are fine to coarse grained, well sorted, quartzose and partially bentonitic. Scollard sandstones have generally more quartz, coarser grain size, less feldspar and less bentonite than the underlying Edmonton Group (Sternberg, 1947; Irish, 1970). Gibson (1977) suggested it is mineralogically and texturally like the Horseshoe Canyon Formation of the Edmonton Group but Allen and Sanderson (1945), Sternberg (1947) and Irish (1970) related the petrography of the Scollard more closely to the Paskapoo. Sternberg (1947) listed analyses of three lower Scollard samples indicating 75-85% of grains in the fine to coarse sand sizes and domination of quartz. Khidir and Catuneanu (2003) described Scollard sandstones as lithic arenites to sublitharenites and provided abundant detail on the diagenetic evolution of these rocks. Locally, there is a heavy calcareous cement and the mudstones are very bentonitic (Gibson, 1977). In Cypress Hills, sandstones in the Frenchman Formation are well sorted, feldspathic, bentonitic and have up to 30% volcanic rock fragments (Furnival, 1950).

Paleocurrents

There is very little paleocurrent data published for the Scollard. The clastic wedge thickens to the west and southwest (Elliot, 1960; Jerzykiewicz and McLean, 1980; Richardson et al., 1988) presumably indicating the source of much of the clastic sediment. Mack and Jerzykiewicz (1989), Jerzykiewicz and Labonte (1991) and Jerzykiewicz (1997), working in the central Foothills, found that the basal Entrance Conglomerate yields unimodal northeasterly paleoflow from pebble imbrication, whereas trough crossbedding in the overlying Coalspur yields a bimodal distribution of paleoflows: to the northeast (ie. perpendicular to depositional trend) and to the southeast (ie. longitudinal to depositional trend). A more detailed treatment of data in the Foothills by Jerzykiewicz and Labonte (1991), indicates dominantly northeastward transport in the more coarse grained Lower Coalspur/Willow Creek (a result comparable to that obtained from trough crossbedding at Cowley by Jerzykiewicz and Norris, 1992), and variable eastward and southward transport in the coal-bearing upper Coalspur/Willow Creek. This may suggest a position more proximal to thrust slice sedimentary sources for the former, and more distal from sedimentary sources for the latter where a longitudinal paleodrainage system was present. In Montana and North Dakota, Tamm et al. (1991) recorded paleoflows to the south and southeast in the lower Hell Creek Formation (lower Scollard-equivalent).

Resource Potential

The Scollard Formation coal zones offer clear potential for seam mining and for coal-bed methane. The geology of these seams was detailed by Richardson et al. (1988). An established, but immature, shallow gas play was described by Hamblin and Lee (1997) for the Scollard/Willow Creek basal fluvial sandstones of central and southern Alberta (Fig. 3). Likewise, the sandstone bodies of these units, where shallow enough, may harbour significant groundwater potential. Recent reconnaissance work on radioactive anomalies in Willow Creek Formation sandstones of southern Alberta suggest there may be potential for uranium occurrences (Matveeva and Anderson, 2007; Matveeva and Kafle, 2009).

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List of Figures

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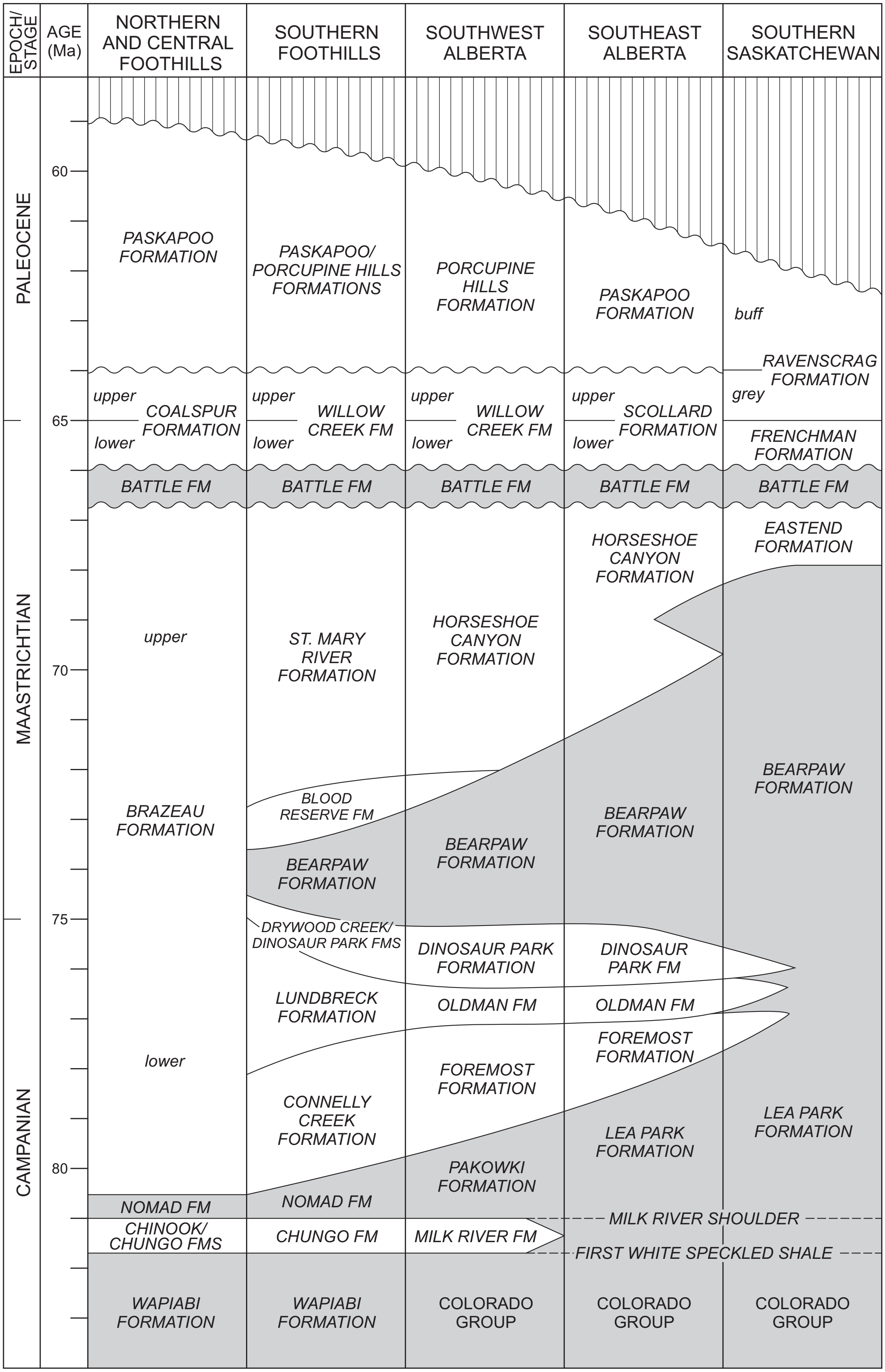

Figure 1. Simplified correlation chart for Upper Cretaceous–Tertiary strata, Alberta–Saskatchewan

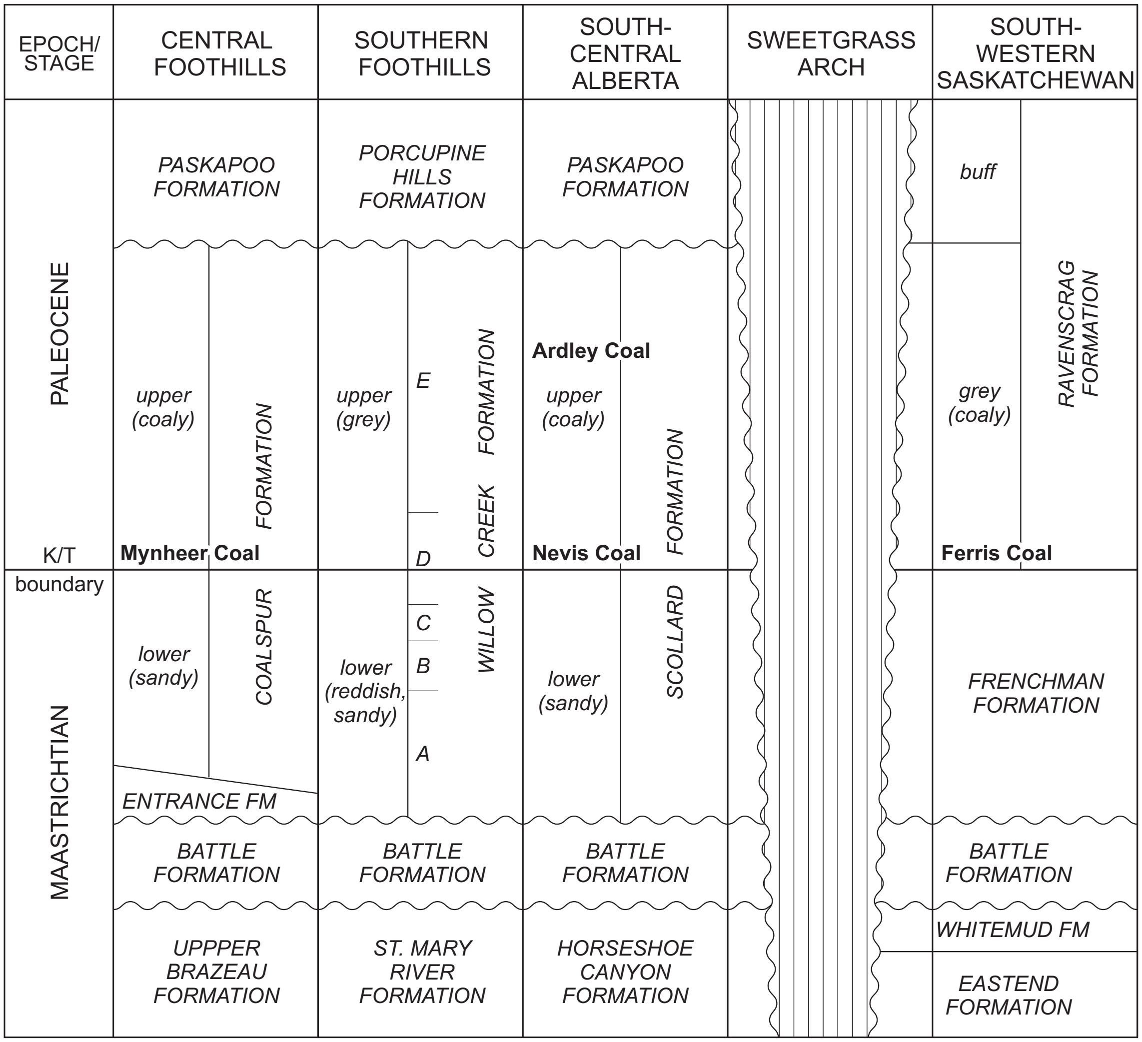

Figure 2. Detailed correlation chart for Scollard–Willow Creek–Coalspur (and equivalents) strata, Alberta–Saskatchewan

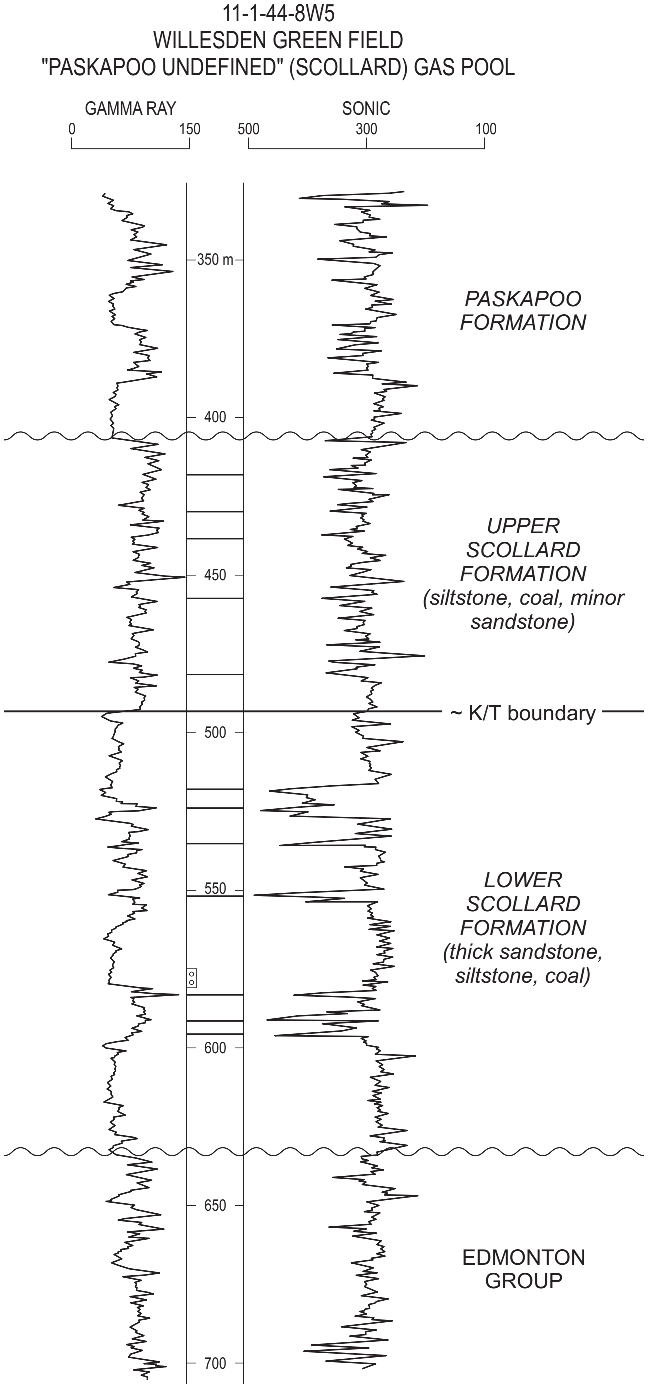

Figure 3. Internal stratigraphy and typical geophysical log signature of the subsurface Scollard Formation (from Hamblin and Lee, 1997).