AER/AGS Open File Report 2015-01

Synthesis of a Post-Laramide Stratigraphic Framework of the South Saskatchewan River Basin, Alberta, in Support of Hydrostratigraphic Modelling

AER/AGS Open File Report 2015-01

Synthesis of a Post-Laramide Stratigraphic Framework of the South Saskatchewan River Basin, Alberta, in Support of Hydrostratigraphic Modelling

G. Hartman

Alberta Energy Regulator
Alberta Geological Survey

May 2015

ISBN 978-1-4601-0138-4

If you use information from this publication in other publications or presentations, please acknowledge the AER/AGS. We recommend the following reference format:

Hartman, G. (2015): Synthesis of a post-Laramide stratigraphic framework of the South Saskatchewan River Basin, Alberta, in support of hydrostratigraphic modelling; Alberta Energy Regulator, AER/AGS Open File Report 2015-01, 36 p.

Published May 2015 by:
Alberta Energy Regulator
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, AB T6B 2X3
Canada

Tel: 780.638.4491
Fax: 780.422.1459
E-mail: AGS-Info@aer.ca
Website: www.ags.gov.ab.ca

Contents

Tables

Figures

Acknowledgements

I thank my colleagues at the Alberta Geological Survey, Dr. N. Atkinson, L. Andriashek, L. Atkinson, and Dr. M. Grobe, for their constructive reviews. I also thank my colleague Dr. M. Fenton for many helpful discussions.

Abstract

An extensive literature review has enabled the synthesis of a post-Laramide stratigraphic framework of the South Saskatchewan River Basin (SSRB) in Alberta. This stratigraphy is the product of nearly continuous tectonic-fluvial processes (uplift, incision, and lateral planation) that have been punctuated by glacial events of both montane and continental provenance. The broad architecture of the landscape itself is a series of nested planation surfaces, including older remnant uplands and younger incised valleys, that represent an inverted stratigraphic column by which the relative stratigraphic position of the nonglacial deposits that mantle the surfaces may be assessed. The distribution and age determinations of glacial deposits that are intercalated among the planation surfaces complement the nonglacial stratigraphy such that both glacial and nonglacial stratigraphies can be integrated in a single post-Laramide stratigraphic framework for the region.

Conceptualization of the post-Laramide stratigraphic framework as an integrated product of nonglacial and glacial processes and recognition of the stratigraphic significance of the landscape architecture is shared between recent stratigraphers (post-1985) and pioneering geologists who first described the study area (pre-1955). In the intervening period, however, a radically different stratigraphic framework became the paradigm. In this alternate stratigraphic framework, tectonic-fluvial development of the study area was complete prior to the first glaciations. Consequently, the nonglacial and glacial stratigraphies are not integrated and cannot provide geometric or chronological references for one another.

This literature review shows that stratigraphies based on the alternate, non-integrated stratigraphic framework have not withstood scrutiny. Remarkably, however, stratigraphies developed prior to 1955, which are based on an integrated stratigraphic framework, are broadly similar to the current (post-1985) stratigraphies. The accomplishment of the earliest period of stratigraphic investigation is attributed to conceptualization of the stratigraphic framework of the SSRB as an integrated product of tectonic-fluvial development punctuated by glaciation.

The Alberta Geological Survey intends to develop three-dimensional hydrostratigraphic models of the subsurface within the SSRB. It is anticipated that an integrated stratigraphic framework in which the stratigraphic significance of the landscape architecture is recognized will help constrain interpretation of post-Laramide sediments and corresponding hydrostratigraphic units in these models.

1 Introduction

This report provides a synthesis of the post-Laramide stratigraphic framework[1] of the South Saskatchewan River Basin (SSRB; Figure 1) in Alberta based on an extensive literature review. The framework is intended to provide context for three-dimensional (3-D) hydrostratigraphic geological models of the post-Laramide sediments within the SSRB, which are being constructed by the Alberta Geological Survey (AGS) as part of the Provincial Groundwater Inventory Program (PGIP).

The post-Laramide stratigraphy of the study area has been extensively studied by numerous researchers for almost 130 years following the initial mapping expeditions of the Geological Survey of Canada. The reasons for such extensive study include

- definition of the southwest margin(s) of the continental[2] ice sheet during the last, and potentially older, glaciations;
- correlation of the southwest margin(s) of continental ice sheets with the established glacial stratigraphy of the mid-continent (Chamberlin, 1896);
- establishment of continental and montane[3] glacial stratigraphies and investigations of the postulated "ice-free corridor" (Johnston, 1933);
- establishment of a nonglacial stratigraphy, particularly for fluvial sediments capping erosional remnants above the modern prairie surface and also within buried valleys;
- recognition and investigation of large glacial flow features which terminate in southern Alberta where a complex succession of sedimentary facies has been deposited;
- accessibility and proximity to population centres, especially at the end of the 19th and the first half of the 20th centuries; and,
- a relative abundance of exposed stratigraphic sections, particularly where modern rivers have incised large buried valleys exposing the sediments captured within them.

Notwithstanding extensive study of the SSRB, stratigraphic interpretations of this region remained contested and controversial.

The most controversial aspects of the stratigraphy include the number, extent, and chronology of montane and continental glaciation(s) across the region and the origin and chronology of sand and gravel deposits associated with various generations of fluvial erosion/deposition that occur across isolated bedrock uplands and the contemporary prairie surface, as well as along the floors of buried valleys.

1 In this report, the term "stratigraphic framework" refers to the stratigraphic position of geological events that affected the study area and the general distribution of associated deposits and landforms.

2 The term "continental" is used in this report to identify continental ice sheets sourced near Hudson Bay. In this usage, the term is synonymous with "Laurentide" in reference to Wisconsinan-aged continental glaciations (Fulton and Prest, 1987; Dyke et al., 1989). During the last (late Wisconsinan) glacial maximum, the western Interior Plains were glaciated by ice sourced at the Keewatin ice divide located in the west shore of Hudson Bay (Dyke and Prest, 1987). Therefore, with respect to the last glaciation, the term "continental" is also synonymous with "Keewatin" or "Keewatin Sector."

3 Bobrowsky and Rutter (1992) noted that the term "montane" should be restricted to locally sourced ice, while "Cordilleran" should refer only to ice of a complete Cordilleran glaciation (extending from the Coast Mountains to the Rockies with an ice divide centred over the plateaus that separate both ranges). However, in many reports on the glacial history of the Rocky Mountain front, the distinction between the two types of western-sourced ice is not made. Therefore, the term "montane" glaciation is used in this report to refer to any significant mountain glaciation, including complete Cordilleran glaciations, which generate piedmont lobes that extend east of the mountain front, whether the ice divide is centred over or west of the Rocky Mountains.

Figure 1. SSRB study area.

In establishing a conceptual post-Laramide stratigraphic framework for the SSRB, these controversies are addressed in this review. However, the framework is based only on previous research in which interpretations are made in full consideration of alternative hypotheses.

1.1 Objectives

The objective of this report is to synthesize a conceptual post-Laramide stratigraphic framework of the SSRB based on a literature review. The stratigraphic framework will provide context for 3-D hydrostratigraphic models that will be used in ongoing AGS projects.

1.2 Study Area

The SSRB study area (Figure 1) is predominantly defined by the South Saskatchewan River and Milk River basins in Alberta. The political boundaries between Alberta, Saskatchewan, and Montana provide the east and south boundaries of the study area, while the Rocky Mountain front[4] provides

4 The Rocky Mountain front in southern Alberta is the generally conspicuous topographic break between the eastern margin of the Rocky Mountains and adjacent foothills (Beaty, 1975; Osborn et al., 2006) and is coincident with the boundary between the Rocky Mountains and Rocky Mountain Foothills physiographic regions mapped by Pettapiece (1986; Figure 2).

the west boundary. The Rocky Mountain Foothills are included in the study area (Figure 2), but the mountain headwaters portion of the South Saskatchewan watershed has been excluded for two reasons: (1) mountain geology is complex and difficult to model and (2) groundwater use in the mountains is negligible as this area is only lightly developed. The largest population centres in the SSRB are Calgary, Lethbridge, and Medicine Hat (Figure 1 and Figure 2).

1.3 Bedrock Geology and Physiography

The bedrock geology of Alberta has been mapped by Prior et al. (2013). All bedrock units which subcrop within the SSRB study area are included within the foreland basin succession of the Western Canada Sedimentary Basin (Price, 1994). Price (1994) broadly outlined the geological history of this succession as being deposited in a subsiding foreland basin that was isostatically depressed by the adjacent, tectonically thickened fold and trust belt, which was the dominant source of basinal sediments. Following the culmination of the Laramide Orogeny (early Eocene; Pana and van der Pluijm, 2014) and a change from a transpressional to a transtensional tectonic regime, the basin was isostatically uplifted, inducing widespread erosion. Estimates of the total thickness of sediment removed by erosion in the SSRB range between 7 km in the Front Ranges of the Rocky Mountains (Figure 2; Osborn et al., 2006) to 1–2 km in the plains (Nurkowski, 1984). Bedrock deformation associated with the fold and thrust belt is restricted to the western edge of the study area (Prior et al., 2013).

The bedrock geology of southern Alberta underpins its physiography, which comprises three major physiographic regions: the Rocky Mountains, the Rocky Mountain Foothills, and the Interior Plains

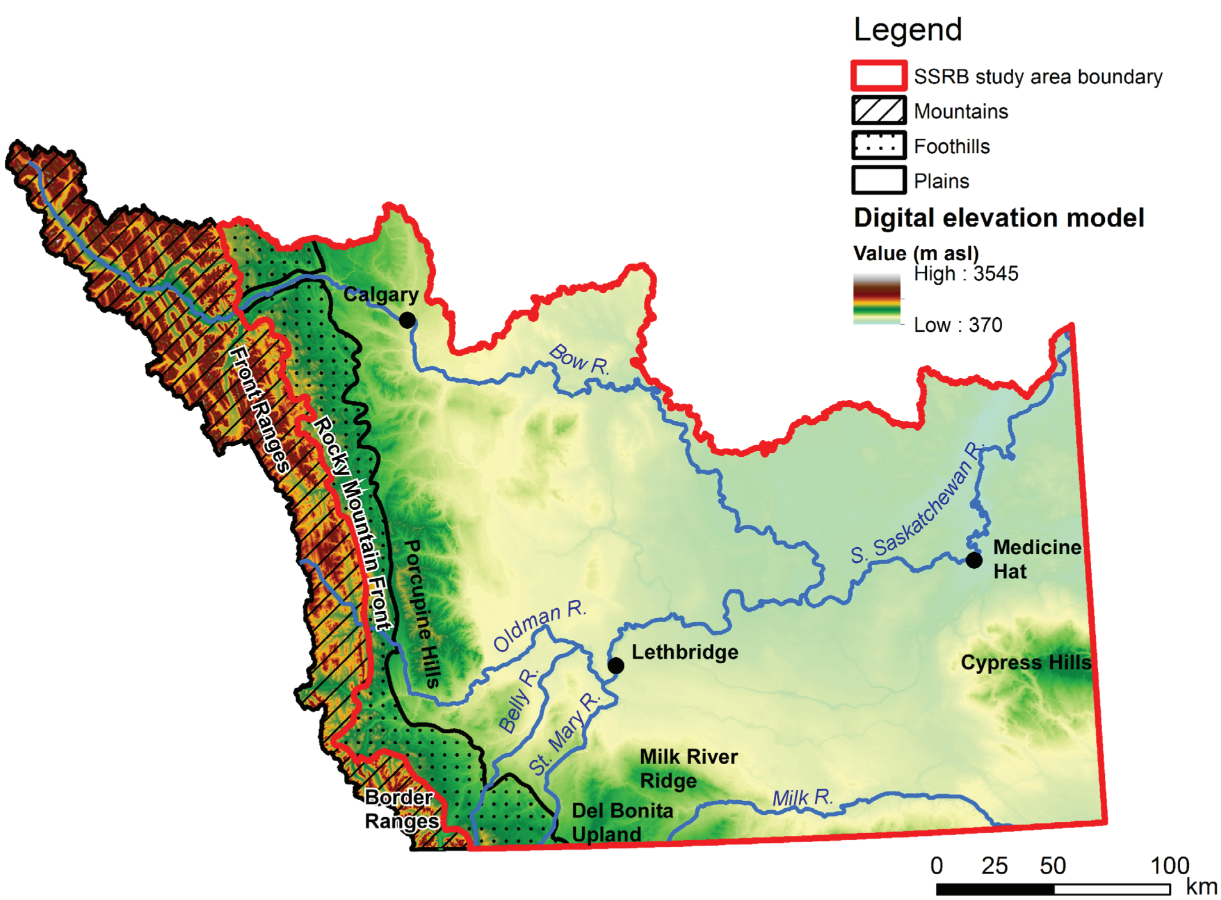

Figure 2. SSRB physiography

(Bostock, 1970; Pettapiece, 1986; Figure 2). Elevation and relief are greatest in the mountains and lowest in the plains (Pettapiece, 1986). Regional slope descends northeastwards across the study area.

The major tributaries of the South Saskatchewan River are the Bow, Oldman, Belly, and St. Mary rivers (Figure 1 and Figure 2). The headwaters of the Milk River lie in Montana, and the river drains back into Montana at Alberta's southern border. The South Saskatchewan River and Milk River watersheds are separated by a continental drainage divide across the Cypress Hills and Milk River Ridge (Figure 1 and Figure 2) that separates the Hudson Bay and Gulf of Mexico drainage basins respectively.

1.3.1 The Rocky Mountains

West of the study area, the Rocky Mountains rise sharply, forming a region of high relief including the Border and Front ranges, which range in elevation between 1400 and 2700 m asl (metres above sea level) and between 1200 and 3300 m asl, respectively (Figure 2; Pettapiece, 1986).

The Rocky Mountains are the exhumed surface representation of highly deformed bedrock where crustal shortening of up to tens of kilometres on major thrust faults have emplaced older, hard, Paleozoic rock above younger, soft, Mesozoic strata (Beaty, 1975; Osborn et al., 2006). These tectonic processes have been overprinted by fluvial and glacial erosion, which have incised and sculpted the mountains, forming the spectacular physiography of the modern landscape (Osborn et al., 2006).

The Rocky Mountains have exerted a strong influence on the study area in the geological past and continue to do so at present. Material eroded from the mountains has significantly contributed to the formations that underlie the foothills and plains physiographic regions, and mountain-building processes uplifted, deformed, and tilted those strata to varying extents (Osborn et al., 2006). In the postorogenic period after the early Eocene (Pana and van der Pluijm, 2014), isostatic uplift of the mountains, foothills, and adjacent plains influenced drainage patterns and erosion/deposition cycles within the study area (Osborn et al., 2006). At present, the headwaters of the major rivers that traverse the study area are located in the mountains with the exception of the Milk River, which originates in the Montana foothills. Permanent snowfields and glaciers also occur within the mountains, some of which supply the Bow River drainage in the northwestern part of the study area. Importantly, from the perspective of post-Laramide stratigraphy, montane glaciations have been sourced in or west of the Rocky Mountains.

1.3.2 The Rocky Mountain Foothills

The western part of the study area falls within the Rocky Mountain Foothills physiographic region and comprises rolling south-to-southeast-trending ridges (1200 to 1800 m asl; Pettapiece, 1986; Figure 2). The western boundary of the foothills is marked by the Rocky Mountain front, while the eastern limit is gradational with the plains (Beaty, 1975; Osborn et al., 2006).

The Rocky Mountain Foothills are underlain by folded and thrusted strata, although, unlike the Rocky Mountains, the magnitude of crustal shortening and uplift is much less (Beaty, 1975). The physiography of the foothills reflects this structure and is due to differential erosion of the upturned strata whereby the ridge crests comprise more resistant sandstones, and the intervening valleys are formed of less resistant rocks (Osborn et al., 2006).

1.3.3 The Interior Plains

The largest part of the SSRB falls within the Interior Plains physiographic region (Figure 2). The plains are generally characterized by lower elevation (600 to 1100 m asl in the SSRB; Pettapiece, 1986), and relief is provided mainly by the features of glacial deposition and erosion (typical local relief of 20 to

100 m; Osborn et al., 2006). However, Osborn et al. noted that greater elevation and relief is found in the Porcupine Hills (1800 m asl; Figure 2) and in two general situations: (1) where erosional remnants of old fluvial plains are elevated relative to the general plains surface and (2) where trunk valleys are incised below it (by up to 100 m in the SSRB). Within the SSRB, the largest and most significant elevated erosional remnants include the Cypress Hills (1470 m asl) and Del Bonita upland (1435 m asl; Figure 2).

The transition from foothills to plains is gradational and difficult to recognize (Beaty, 1975). Osborn et al. (2006) noted that a boundary between foothills and plains could be defined based on either geomorphic or geological criteria. A geomorphic boundary would separate regions in which topography is influenced by underlying structure (in the form of linear ridges trending south-southeast) from regions in which topography shows no organized structural influence. On the other hand, a geological boundary would separate regions in which the underlying strata are deformed (folded and faulted) from regions in which they are not. A geological boundary would not be visible at surface and would require subsurface information to define. With the exception of the Porcupine Hills, which are underlain by undeformed strata and directly abut structurally influenced topography, a geological boundary would generally lie to the east of the geomorphic boundary (Osborn et al., 2006). In this document the geomorphic boundary, as mapped by Pettapiece (1986; Figure 2), is favoured as it is visible from surface and does not require subsurface information to be defined.[5]

2 Review of the Post-Laramide Stratigraphy Literature

The post-Laramide stratigraphy of the SSRB is a product of nonglacial and glacial processes, which impart different geomorphic and stratigraphic signatures. Nonglacial processes represent the fluvial response to episodic cycles of tectonic uplift and stability and are dominated by incision and lateral planation (Osterkamp et al., 1987). These processes commenced following the end of transpressional tectonics (latest Paleocene to middle Eocene; Leckie, 2006; Pana and van der Pluijm, 2014). While much of the relief of the plains was established during the Tertiary[6] (Vreeken and Westgate, 1992; Barendregt et al., 1997; Leckie, 2006), incision continues to the present (Osborn et al., 2006). Younger planation surfaces[7] are topographically lower than, and are thus incised through, older surfaces, resulting in a plains landscape composed of dissected remnant fluvial planation surfaces lying at successively lower elevations

5 Pettapiece (1986) defines the Southern Alberta Uplands (1000 to 1650 m asl in the SSRB) as intermediate between foothills and plains. The Southern Alberta Uplands include the Porcupine Hills and elevated erosional remnants, as well as uplands that flank these features. However, other authors typically include the same features within descriptions of the plains (Alden, 1932; Vonhof, 1969; Beaty, 1975; Edwards and Scafe, 1994; Leckie, 2006; Osborn et al., 2006). In this document, the Southern Alberta Uplands are not recognized as a separate physiographic region but are included within the plains.

6 The Tertiary Period traditionally refers to the interval between the Cretaceous and Quaternary periods (Head et al. 2008; Knox et al., 2012). However, the International Commission on Stratigraphy (ICS) abandoned the Tertiary term in 1976 and has divided this interval into the Paleogene and Neogene periods (Cowie and Bassett, 1989; Head et al., 2008). In North America, the Tertiary Period, as described by Palmer (1983) and Salvador (1994) continued to be recognized by the US Geological Survey and the Geological Society of America (Head et al., 2008). Internationally, the Tertiary has endured as an informal term having never been eliminated by the ICS (Knox et al., 2012). In this document, following its use in the literature reviewed, the Tertiary Period refers to the interval between the Cretaceous and Quaternary periods and is used alongside Paleogene and Neogene as per Palmer (1983) and Salvador (1994).

7 Planation surfaces are synonymous with Alden's (1932) "benches" that he defined as including plateau, mesa, ridge, and terrace features where the underlying strata are beveled by fluvial erosion and not simply the stripping of soft shale from hard sandstone.

between the top of the Cypress Hills monadnock and the floors of buried valleys (Leckie, 2006). Glacial processes generated by montane and continental ice sheets, which collectively covered most of the study area, are recognized by the sediment-landform assemblages they left behind. The earliest montane glaciations may have reached the study area in the late Pliocene (Cioppa et al., 1995). Continental ice did not reach the study area until the mid- to late Pleistocene (Proudfoot, 1985; Jackson et al., 2008; Jackson et al., 2011; Barendregt et al., 2012).

After the late Pliocene, when glaciation first affected the study area (Cioppa et al., 1995), the nonglacial and glacial stratigraphies overlap chronologically. The two stratigraphies also overlap geometrically as the nonglacial stratigraphy is represented in the broad bedrock physiography upon which the glacial stratigraphy is superposed. Consequently, the two stratigraphies are integrated in time and space, and each can be used to provide a geometric and relative chronological reference upon which to structure the other. When considered together, the two stratigraphies, nonglacial and glacial, provide a better understanding of the complete post-Laramide stratigraphic framework than when each is considered independently.

Although our most recent understanding of the post-Laramide stratigraphic framework of the SSRB includes integrated nonglacial and glacial stratigraphies, these components have not always been treated together. Between approximately 1955 and 1985, nonglacial and glacial stratigraphic components were typically treated separately. This division had a profound impact on the development of the post-Laramide stratigraphy as a whole. During this period, nonglacial processes were seen as predating, and thus distinctly separate from, glacial processes. Conceptualization of the post-Laramide stratigraphy as a linear progression from dominantly nonglacial to dominantly glacial processes prevented the use of the nonglacial stratigraphy as a geometric and relative chronological reference with which to structure the glacial, or vice versa. In the development of the post-Laramide stratigraphic framework of the SSRB, this period stands out as distinctly different from those preceding or succeeding it and facilitates grouping the literature by publication date around it. Therefore, the literature encompassing the post-Laramide stratigraphy of the SSRB can be divided by publication date into three periods: pre-1955, 1955 to 1985, and post-1985.

In addition to markedly different conceptualizations of the post-Laramide stratigraphy, there were other factors that contributed to the significant differences in stratigraphic interpretation between the three periods, including differing objectives, available stratigraphic assessment methodologies, availability and accuracy of dating methods, and the availability of surface and subsurface data.

2.1 Pre-1955

The first period of stratigraphic investigation occurred before 1955 and was dominated by regional geological surveys. In these surveys, the post-Laramide stratigraphy was sometimes of secondary importance to bedrock or economic geology. This period predates the development, or widespread availability, of many of the methods of modern stratigraphic analysis. Indeed, glacial theory (c.f. Agassiz, 1864) only became generally accepted during the early part of this period. One prominent theme at this time was the attempt of a systematic correlation (in some cases without supporting evidence) with the established four-fold glacial chronology of middle North America (Alden, 1929).

Importantly, during this period, the post-Laramide stratigraphy was generally not divided into primarily glacial or nonglacial components. The nonglacial and glacial stratigraphies were integrated such that each provided a geometric and relative chronological reference with which to structure the other. Later authors tended to build on the observations of their predecessors so that stratigraphic concepts developed linearly towards a collective framework by the end of this period.

2.1.1 Stratigraphic Framework

Early stratigraphic studies of southern Alberta and surrounding areas (Figure 3) recognized that the physiography of the region comprised a series of nested fluvial planation surfaces where the dissected remnants of older surfaces are topographically higher than younger, more continuous surfaces (McConnell, 1885; Calhoun, 1906; Collier and Thom, 1918; Alden, 1932; Rutherford, 1937; Horberg, 1954). These planation surfaces were attributed to episodic cycles of uplift, fluvial incision, and lateral planation between the Paleocene (the stratigraphic age of the youngest plains rocks involved in folding) and the late Pleistocene (Alden, 1932). These nested surfaces and ages of overlying nonglacial deposits underpinned the nonglacial stratigraphy of the study area. The nonglacial stratigraphy was integrated with the glacial stratigraphy based on the geometric and relative chronological relationships between the surfaces and glacial deposits of montane and continental provenance. The result was a stratigraphic framework for all post-Laramide deposits. The major components of the stratigraphic framework are described below (see also Table 1 and Figure 4):

The highest and oldest surfaces are represented by flat-topped uplands and monadnocks that are commonly capped by coarse cobble-boulder gravel. These features were interpreted as the floors of former valleys that are elevated relative to the surrounding plains due to differential erosion between the gravel-armoured valley floors and the adjacent unprotected soft sedimentary bedrock (McConnell, 1885; Alden, 1932). Lower, younger surfaces include the modern plains surface and valleys incised below it. Although the highest and oldest surfaces commonly support gravel, the formation of a planation surface was considered a regional-scale process in which all drainage elements contribute to the final result (Alden, 1932; Warren, 1939). Therefore, planation surfaces include areas with and without gravel.

Based on relative elevation, four groups of fluvial planation surfaces were recognized[8] (Calhoun, 1906; Collier and Thom, 1918; Alden, 1932; Figure 4). Each elevational group may comprise several surfaces within a small vertical range that is significantly higher than the next group below. The highest planation surface, named the Cypress Plain (Alden, 1932), comprises the Cypress Hills monadnock (Figure 3) in southeastern Alberta and southwestern Saskatchewan. The second-highest planation surface was named the Flaxville Plain or No. 1 Bench (Alden, 1932) and is represented by lesser uplands, ridges, and monadnocks, including the Flaxville uplands, Hand Hills, Boundary Plateau, parts of Milk River Ridge, the Del Bonita upland, and Mokowan Butte (Figure 3). The modern plains represent the third-highest planation surface and were named the No. 2 Bench (Alden, 1932). This surface is the most extensive in the region. Lastly, the lowest surface, named the No. 3 Bench (Alden, 1932), occurs along the floors of paleovalleys incised below the plains (Figure 3).

The surface of the Cypress Hills is mantled by the Cypress Hills Formation boulder-cobble conglomerate (Russell and Landes, 1940) from which Oligocene to early Miocene fossils were recovered (identified

8 In the literature, the elevations of fluvial planation surfaces—as represented by elevated, monadnock-type erosional remnants, plateaus, mesas, ridges, terraces, benches, incised paleovalleys, or the plains surface—are cited and compared, and long-distance correlations between surfaces are made. It is important to note that the long profiles of these surfaces are inclined (or possibly curvilinear) away from the mountains, and a direct comparison of point elevation of two surfaces (or remnants thereof) that are distal to one another in a direction perpendicular to the mountain front is not informative unless their distance from the mountain front and the long profile geometry of the surface is also considered. Furthermore, the total amount of uplift and erosion appears to lessen in a northward direction across Alberta (Edwards and Scafe, 1994), requiring that comparisons of point elevation of two surfaces also be constrained in a direction parallel to the mountain front. In practice, definition of the regional geometry of incomplete (eroded or buried) surfaces is difficult, and long-distance correlation of surfaces may be equivocal (Vreeken and Westgate, 1992). Therefore, following the literature, four groups of planation surfaces are defined relative to the modern plains.

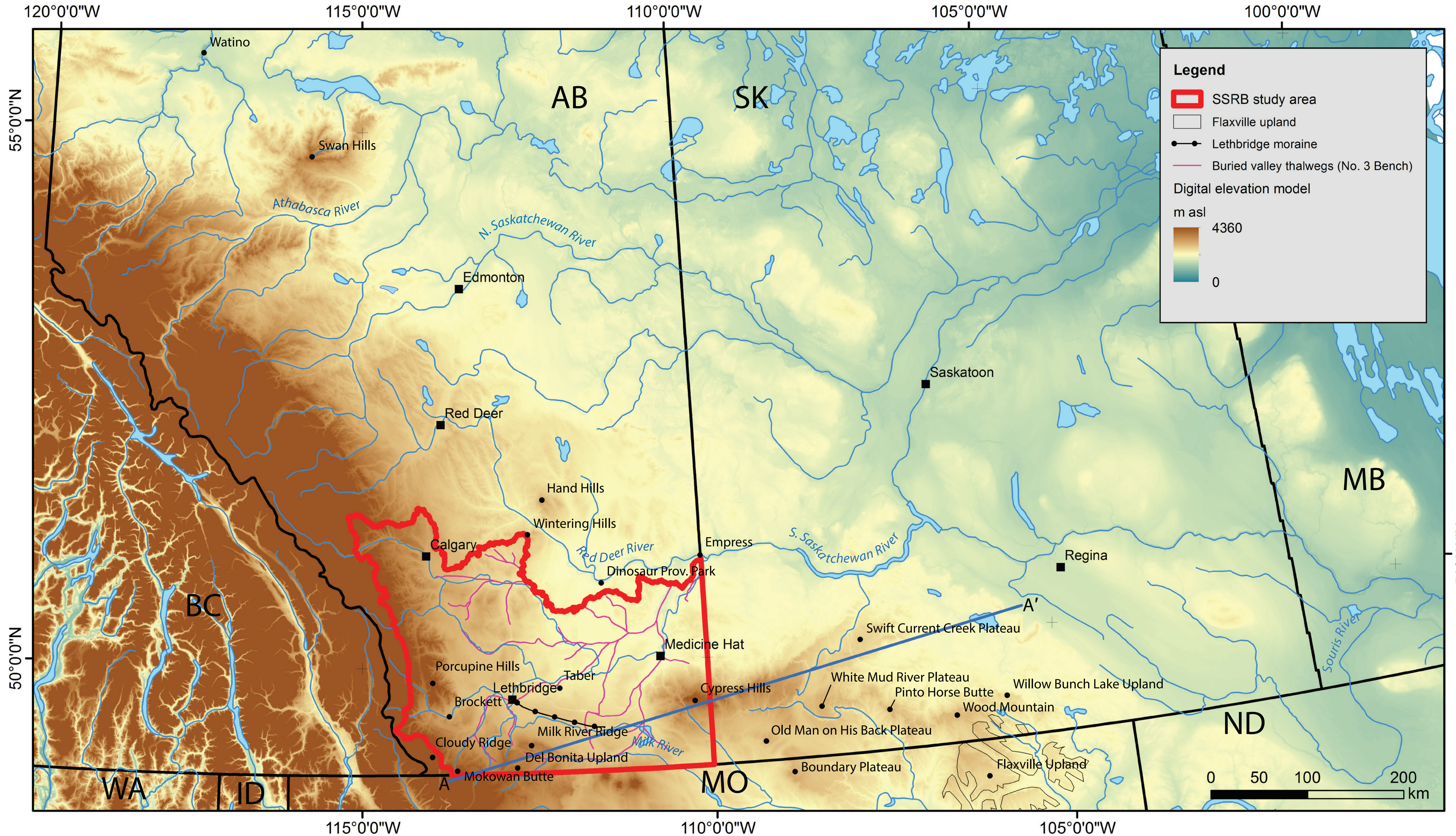

Figure 3. SSRB study area and surrounding Interior Plains showing localities and features referred to in the text. Line of section A-A′ corresponds with diagrammatic cross-sections in Figures 4, 5, and 6. Buried valley thalwegs based on Geiger (1968). Lethbridge moraine based on Horberg (1952).

Table 1. Stratigraphic framework pre-1955.

Surface	Features / Localities	Nonglacial Deposits	Glacial Deposits	Age
Swift Current Creek paleovalley	Swift Current Creek Plateau	Swift Current Creek Beds		late Eocene
Cypress Plain	Cypress Hills	Cypress Hills Formation		Oligocene to early Miocene
Flaxville Plain (No. 1 Bench)	Flaxville upland, Hand Hills, Boundary Plateau, parts of Milk River Ridge, Del Bonita upland, Mokowan Butte	Flaxville Formation, Hand Hills gravel, Boundary Plateau gravel, Del Bonita gravel		Miocene to early Pliocene
No. 2 Bench	modern plains surface	Saskatchewan gravels	montane tills (Kennedy drift)	established by early Pleistocene
No. 3 Bench	buried valleys	Saskatchewan gravels	early and late Wisconsinan montane till; late Wisconsinan continental till	established by late Pleistocene
modern base level	modern major river valleys	modern alluvium		Holocene

by E.D. Cope [1891] in McConnell, [1895]). The deposit is dominated by resistant lithologies including quartzite, chert, arkose, limestone, and dolomite (Leckie, 2006). Of these, quartzite is most common at >90% based on clast count (Leckie and Cheel, 1989). The lithology of the deposit, including minor igneous and metamorphic lithologies, as well as sand mineralogy, suggests source areas in the western Rocky Mountains and volcanic complexes to the south-southwest (Leckie and Cheel, 1989; Edwards and Scafe, 1994). The very coarse gradation of the deposit, compared to gravel capping lower surfaces at similar distance from the mountain front, was attributed to steep paleodrainage gradients (McConnell, 1885; Alden, 1932). Till or glacial erratics are not found on the upper surface of the Cypress Hills, indicating that it has never been glaciated (McConnell, 1885).

The Swift Current Creek Plateau lies adjacent to the northeastern slopes of the Cypress Hills and is approximately 250 m lower (Figure 3). McConnell (1885) recognized that the form of the basal contact of the gravel capping the Swift Current Creek Plateau was a basin or valley and suggested that the feature was eroded and infilled prior to development of the adjacent, higher Cypress Plain. Later, Vonhof (1969) showed that the basal contact was in the form of a valley. McConnell's observation was prescient as the gravel overlying the Swift Current Creek Plateau was later assigned to the upper Eocene based on fossil evidence, indicating that the plateau is the re-excavated basal portion of a paleovalley that predates the Cypress Plain (Russell and Wickenden, 1933; Figure 4). Therefore, the gravel capping the Swift Current Creek Plateau is the oldest post-Paleocene deposit recognized on the plains of southern Alberta,

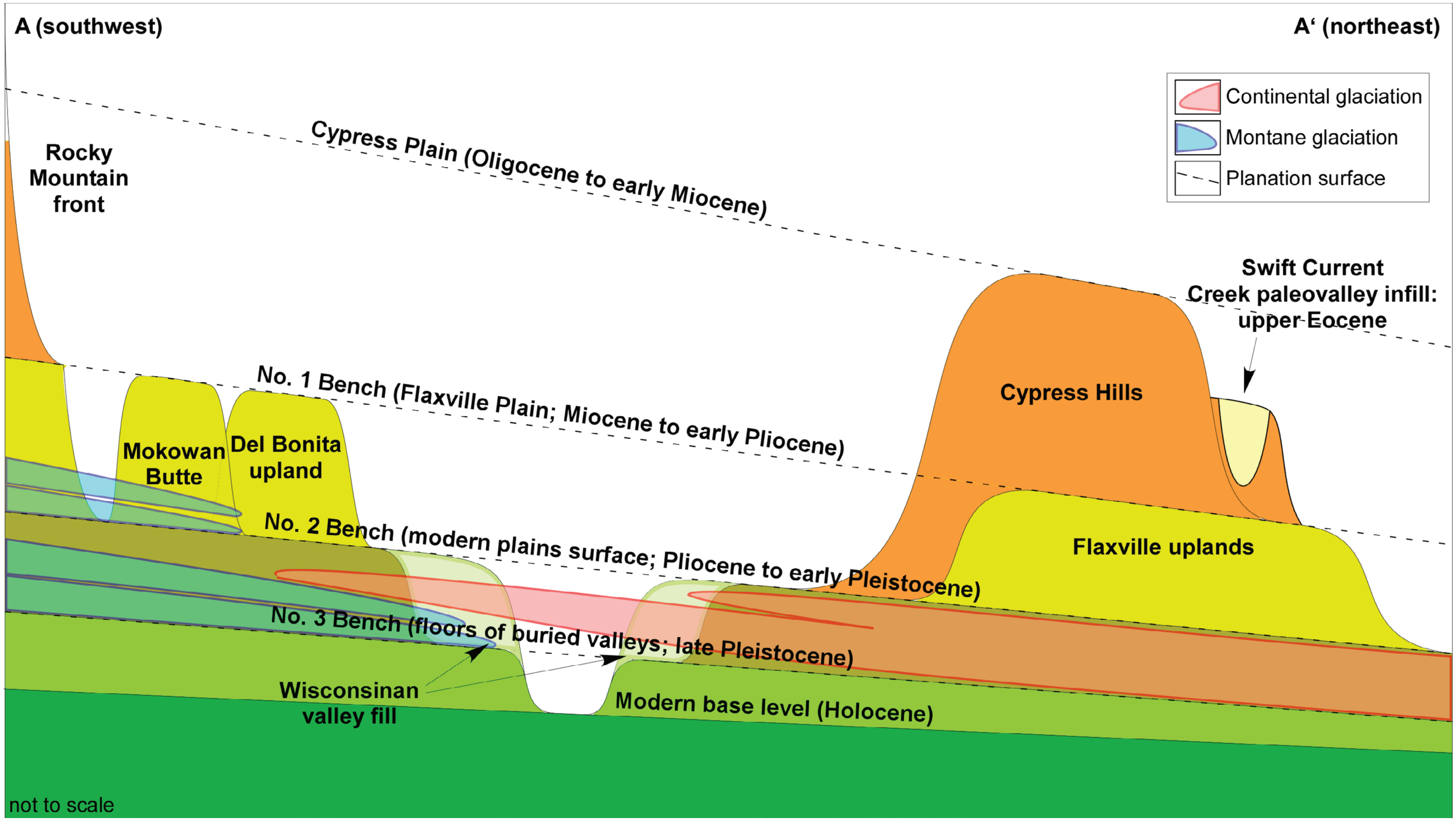

Figure 4. Diagrammatic cross-section A–A′ (Figure 3) showing major elements of the stratigraphic framework from the period pre-1955.

southwestern Saskatchewan, and northern Montana. Russell (1950) named these deposits the Swift Current Creek Beds.[9]

After the early Miocene, the Cypress Plain was uplifted and incised. Fluvial planation resumed at the lower elevation of the Flaxville Plain (Alden, 1932; Figure 4). The Flaxville Plain is mantled by the Flaxville Formation (Taylor et al., 1966) in the Flaxville uplands area (Figure 3) from which Miocene to early Pliocene fossils were recovered (Collier and Thom, 1918). Other remnants of the Flaxville Plain include the Hand Hills (Warren, 1939), Boundary Plateau (Collier and Thom, 1918), parts of Milk River Ridge, the Del Bonita upland, and Mokowan Butte (Alden, 1932; Figure 3). Deposits of the Flaxville Plain are dominated by resistant lithologies including quartzite, chert, and argillite. Minor lithologies include chert-pebble conglomerate and breccia, chalcedony, porphyry, basalt, and limestone (Leckie, 2006). Alden (1932) suggested that the Flaxville Formation was deposited by the ancestral Missouri River, which flowed northwards across the plains to Hudson Bay.

Following further regional uplift prior to the mid-Pliocene, the Flaxville Plain was incised. Fluvial planation resumed at the lower elevation of the No. 2 Bench, which is approximately equivalent to the general surface of the modern plains (Alden 1932; Figure 4). The age of the No. 2 Bench is provided only by the recovery of a single fossil horse tooth that resembles modern species (Collier and Thom, 1918) and by the stratigraphic relationship between remnants of the planation surface near the mountain front and overlying montane tills (Alden, 1932; Horberg, 1954). The tills, being heavily weathered and dissected, were assessed as lower Pleistocene,[10] indicating that the No. 2 Bench was established by that time (Alden, 1932; Horberg, 1954). The montane tills also mantle remnants of the Flaxville Plain near the mountain front (Alden, 1932; Horberg, 1954). Horberg (1954) named the tills the Kennedy drift and associated them with the Kennedy gravels (Willis, 1902), which are widely distributed south of the international border. Although Willis considered the gravels to have a nonglacial genesis, Horberg suggested that the gravels are a distal, glaciofluvial facies of the Kennedy drift.

Regional uplift resulted in incision of the No. 2 Bench. Fluvial planation resumed at the lower elevation of the No. 3 Bench, which comprises a network of broad valleys (Alden, 1932; Figure 4). Within the SSRB, the valleys of the No. 3 Bench are commonly infilled. The floor of the No. 3 Bench is overlain by gravel that is composed entirely of montane lithologies and is devoid of material derived from the

9 The gravel capping the Swift Current Creek Plateau was correlated with the Cypress Hills Formation (which caps the adjacent, higher Cypress Hills) by Christiansen (1959). Vonhof (1969) recognized both deposits as Cypress Hills Formation but informally differentiated them, retaining the name "Swift Current Creek Beds" for the deposit capping the Swift Current Creek Plateau. Storer (1996) reviewed the paleontology of both deposits and showed that they accumulated nearly continuously between the mid-Eocene and early Miocene. Following conventional usage in the literature during each period of stratigraphic investigation, the name "Swift Current Creek Beds" is maintained in the first and second periods (pre-1955 and 1955–1985). In the post-1985 period, both deposits are included in the Cypress Hills Formation.

10 Detailed analysis of the heavily weathered and dissected montane tills (Kennedy drift) was undertaken in the third period of stratigraphic investigation (1985–present) by Karlstrom (1981, 1987, 1988, 2000), Barendregt et al. (1991) and Cioppa et al. (1995). Collectively, these researchers identified up to seven glacial-interglacial cycles ranging in age between late Pliocene and early Illinoian. The Kennedy drift is discussed further in Section 2.3.1.1 below.

Canadian Shield.[11] McConnell (1885) recognized that this deposit predated the first regional incursion of continental ice and named it the South Saskatchewan gravels. Generally, the deposit comprises gravel and sand that overlie bedrock and underlie continental till. It has alternatively been termed Saskatchewan gravels (Dawson and McConnell, 1895) or Saskatchewan gravels and sands[12] (Rutherford, 1937) due to its more widespread distribution and varied composition than originally recognized by McConnell (1885). The genesis of the deposit has been variously interpreted as intermixed preglacial fluvial and montane outwash deposits (Dawson and McConnell, 1895; Rutherford, 1937; Horberg, 1954), and a purely preglacial fluvial deposit (Calhoun, 1906; Alden, 1932).

The Saskatchewan gravels within incised valleys of the No. 3 Bench grade conformably into lacustrine sediments that bear shield clasts near their top (McConnell, 1885). The lacustrine sediments are associated with the formation of an ice advance phase proglacial lake (McConnell, 1885). McConnell interpreted the stratigraphic position of the lacustrine sediments as indicative of deposition immediately prior to the initial advance of continental ice into the region which Horberg (1954) assigned to the late Wisconsinan. West and south of Lethbridge, the Saskatchewan gravels on the No. 3 Bench are directly overlain by Wisconsinan montane till (Dawson and McConnell, 1895; Horberg, 1954; Calhoun, 1906; Collier and Thom, 1918; Alden, 1932). Near the mountain front, Horberg (1954) recognized early and late Wisconsinan montane till on the No. 3 Bench. Age assignment of the montane and continental glaciogenic sediment that infills the incised valleys of the No. 3 Bench to the Wisconsinan suggests that the planation surface was established prior to the late Pleistocene (Calhoun, 1906; Alden, 1932; Horberg, 1954).

Rutherford (1937) redefined the Saskatchewan gravels as simply fluvial or intermixed fluvial and glaciofluvial deposits that are free of material derived from the Canadian Shield and that overlie bedrock and underlie continental till. The definition was not restricted to deposits on the No. 3 Bench; therefore, it does not consider the potential stratigraphic significance of relative elevation differences between deposits. Rutherford recognized the stratigraphic limitation of the definition and suggested that the deposits, being widely distributed and of uncertain genesis, could have been emplaced by different mechanisms at different times. Horberg (1954) noted that in southwestern Alberta, the definition of Saskatchewan gravels (c.f., McConnell, 1885; Dawson and McConnell, 1895) could be applied to deposits with varying distribution and range of possible origins and ages including fluvial deposits on the Flaxville Plain and No. 2 Bench, glaciofluvial deposits associated with outwash from Kennedy drift, and early and late Wisconsinan montane glaciofluvial outwash. Horberg (1954) advocated that the term be discontinued in formal stratigraphic usage.

Wisconsinan-aged tills comprise the youngest major component of the stratigraphic framework established in this period of stratigraphic study. Horberg (1954) noted that both the early and late Wisconsinan montane tills near the mountain front are overlapped by a single late Wisconsinan continental till associated with the most extensive advance of continental ice across the western plains and foothills during Quaternary glaciation. To the northeast of the Lethbridge end moraine (Figure 3), this

11 Distinctive lithologies from the Canadian Shield found within fluvial (or glaciofluvial) gravel deposits are commonly used as indicators of the previous incursion of a continental ice sheet even if till of such an advance has not been recognized. The advance of an eastern ice sheet is the only mechanism by which to transport these clasts up the regional slope of the plains, although they may have been transported along an ice front by ice-marginal drainage or rafted in proglacial lakes.

12 After Rutherford (1937) changed the name of the Saskatchewan gravels to the Saskatchewan gravels and sands, various authors use different variants of “Saskatchewan”, “gravel”, and/or “sand” to name similar deposits. In this report, “Saskatchewan gravels” is used as a collective informal term, whereas “Saskatchewan Gravel” is used when referring to the unit as a formation of the Empress Group as defined by Whitacker and Christiansen (1972).

till underlies a second continental till and is separated from it by the Lenzie silt in the Lethbridge region (Horberg, 1952). Horberg (1952 and 1954) interpreted the silt, upper till, and the Lethbridge end moraine as products of a late Wisconsinan continental re-advance.

2.1.2 Summary

By 1955, the contributions of all workers could be collectively focused to illuminate a single integrated post-Laramide stratigraphy of the SSRB that contained the following elements:

- Post-orogenic development of the Interior Plains commenced with regional uplift and fluvial incision of deep valleys. The valleys were subsequently infilled, as represented by the re-excavated upper Eocene Swift Current Creek Beds of the Swift Current Creek Plateau in eastern Saskatchewan (McConnell, 1885; Russell and Wickenden, 1933).
- During the Oligocene to early Miocene, the Cypress Plain developed across the region by fluvial planation (McConnell, 1885; Alden, 1932).
- After the early Miocene the Cypress Plain was uplifted and incised. Fluvial planation resumed below the Cypress Plain forming the Flaxville Plain, upon which the Miocene to lower Pliocene Flaxville Formation was deposited (Collier and Thom, 1918; Alden, 1932).
- Before the mid-Pliocene, the Flaxville Plain was uplifted and incised. Fluvial planation resumed at the lower elevation of the No. 2 Bench, which is approximately equivalent to the general surface of the modern plains (Collier and Thom, 1918; Alden, 1932). The No. 2 Bench was established prior to the early Pleistocene because it is mantled by Kennedy drift near the mountain front which was assessed as lower Pleistocene in this period of stratigraphic investigation (Alden, 1932; Horberg, 1954).
- Regional uplift resulted in incision of the No. 2 Bench. Fluvial planation resumed at the lower elevation of the No. 3 Bench, which comprises broad valleys (Alden, 1932). These valleys are commonly infilled with a range of glaciogenic facies relating to the advance and retreat of Wisconsinan montane and continental glaciers, indicating that the fluvial surface was established prior to the late Pleistocene (Horberg, 1954). Postglacial fluvial incision has not completely re-excavated the No. 3 Bench, leaving much of it buried.
- The Saskatchewan gravels unit, which in its coarse lower portion is free of shield clasts and thus interpreted as preglacial with respect to continental glaciation (McConnell, 1885), occupies a range of physiographic settings and has been variously interpreted as fluvial, glaciofluvial, or a mix of both. Age assignments of the Saskatchewan gravels range from Tertiary to immediately prior to continental glaciation. Given these uncertainties, Horberg (1954) suggested that the term Saskatchewan gravels be abandoned in formal stratigraphic usage.
- Early and late Wisconsinan montane tills are recognized on the No. 3 Bench at the mountain front and are overlapped by late Wisconsinan continental till (Horberg, 1954). Re-advance of the late Wisconsinan continental ice sheet is recognized by the Lenzie silt and upper till that terminates at the Lethbridge end moraine (Horberg, 1952 and 1954).

At the end of this period of stratigraphic investigation, a post-Laramide stratigraphic framework based on careful, regional-scale observations is interpreted as a product of integrated nonglacial and glacial processes, whereby each respective stratigraphy is used to provide a partial chronological and geometric reference upon which to structure the other. This integrated stratigraphic framework largely resembles our current understanding of the post-Laramide history of the region, despite being developed without modern dating methods or analytical techniques and with limited surface and subsurface information.

2.2 1955 to 1985

The second period of stratigraphic investigation, between 1955 and 1985, is largely characterized by local studies, often of only a few stratigraphic sections. However, the results of these studies were commonly extrapolated across the region. This methodology is intrinsic to the concept of the type section, which adapted traditional bedrock geology correlation techniques to highly heterogeneous and discontinuous glacial deposits. Studies at this time also tended to concentrate only on discrete stratigraphic components rather than addressing the entire succession. Consequently, the stratigraphy was considered a product of dominantly nonglacial processes followed by dominantly glacial ones. The transition from nonglacial to glacial processes was demarcated by the upper portion of the Saskatchewan gravels. Under this conceptualization, the nonglacial and glacial stratigraphies could not provide frameworks upon which to structure one another, and the resultant stratigraphy is markedly different from that developed prior to 1955.

In addition to methodological differences, this period of stratigraphic investigation was characterized by the application of radiocarbon dating methods (c.f., Arnold and Libby, 1949). However, many early radiocarbon dates from the plains were erroneous due to contamination by old carbon (MacDonald et al., 1987) leading to the subsequent modification of stratigraphies based on such dates.

2.2.1 Stratigraphic Framework

Between 1955 and 1985, the post-Laramide stratigraphy was radically revised. During this period, glacial processes were seen as distinctly postdating cycles of tectonic uplift, fluvial incision, and planation that are represented in the broad physiography of the Interior Plains. The nonglacial and glacial stratigraphies, therefore, were not integrated, and each could not be used as a partial chronological or geometric reference upon which to structure the other. A.M. Stalker is the primary architect of the glacial stratigraphy developed in this period. He revised the stratigraphy several times based on new observations and dates, some of which were extrapolated to southern Alberta from distal parts of the plains (Stalker, 1963, 1969, 1976, 1977, 1983; Stalker and Harrison, 1977; Stalker and Wyder, 1983). The final regional stratigraphy from this work (c.f. Stalker and Harrison, 1977; Stalker, 1983) is summarized below (Table 2 and Figure 5):

Stalker (1963, 1968, 1969, 1976, 1983) and Stalker and Harrison (1977) placed the preglacial Saskatchewan gravels at the base of the glacial stratigraphy and suggested that it represents the final deposit of a continuum of fluvial incision, planation, and deposition that initiated with the Oligocene Cypress Hills Formation and terminated at the onset of Pleistocene glaciation. Importantly, in this stratigraphic conceptualization, physiographic development of the plains through regional tectonic uplift, fluvial incision, and planation was complete prior to the first glaciation of southern Alberta by either montane or continental ice. Therefore, the stratigraphic significance of the physiographic bench architecture described by Alden (1932) was not recognized and could not be used as a partial chronological and geometric reference upon which to structure the glacial stratigraphy. Although distinct from gravel deposits overlying the Cypress Plain and Flaxville Plain, it is clear that the Saskatchewan gravels mantle both the No. 2 and No. 3 benches (Figure 5).

According to the stratigraphy of Stalker and Harrison (1977), the initial and most extensive advance of both montane and continental ice into southern Alberta occurred during the Illinoian (Figure 5). Associated deposits include (1) an uppermost limestone-clast-bearing portion of the Saskatchewan gravels within buried incised valleys proximal to the mountain front, interpreted as montane glacial outwash; (2) montane till overlying the Saskatchewan gravels within buried incised valleys west of Lethbridge; (3) Kennedy drift found high across remnant interfluves along the mountain front including, in southwestern

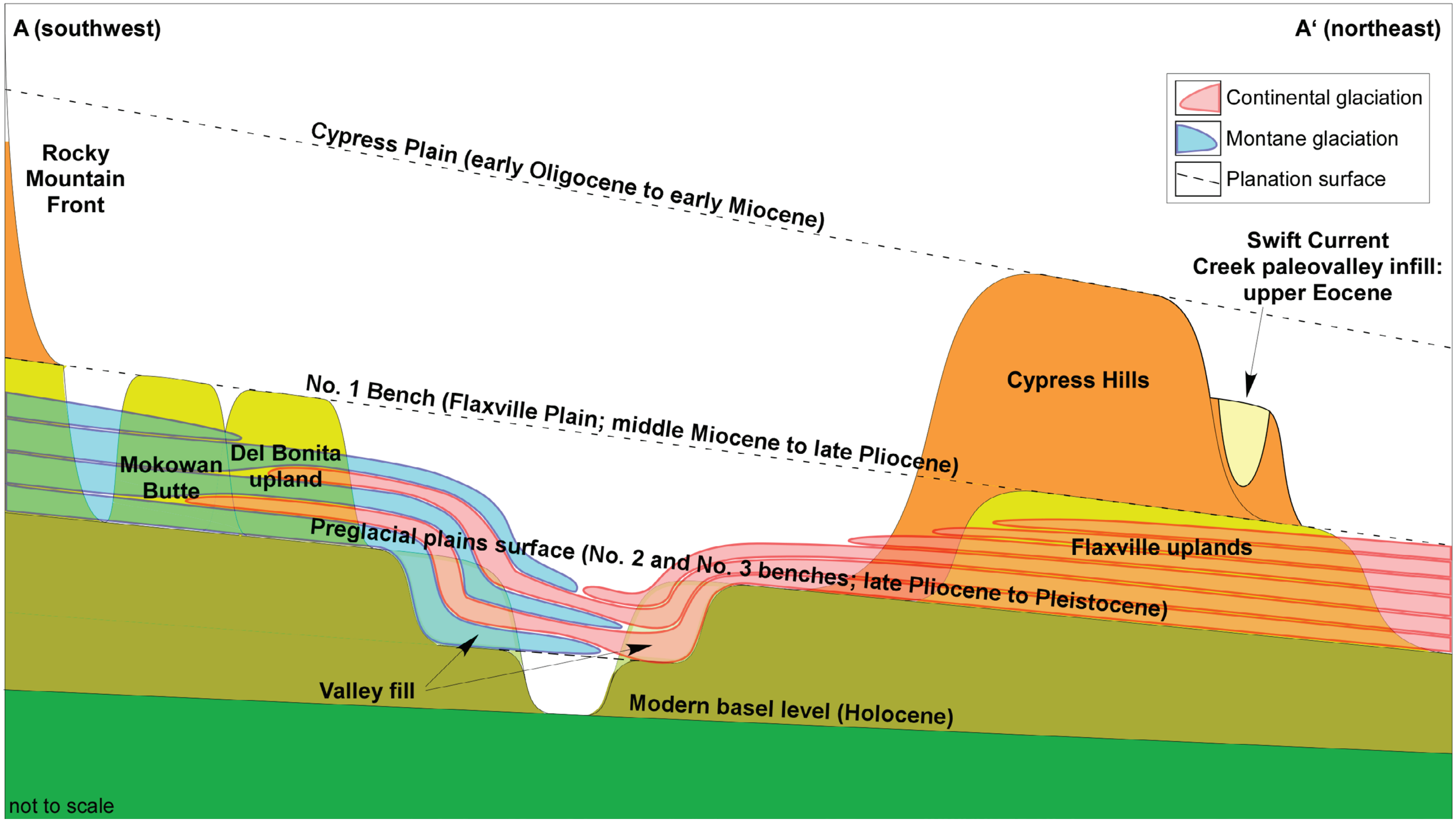

Figure 5. Diagrammatic cross-section A–A′ (Figure 3) showing major elements of the stratigraphic framework from the period 1955–1985.

Table 2. Stratigraphic framework 1955 to 1985.

Surface	Features / Localities	Nonglacial Deposits	Glacial Deposits	Age
Swift Current Creek paleovalley	Swift Current Creek Plateau, Swan Hills (tentative)	Swift Current Creek Beds, lower portion of Swan Hills deposits (tentative)		late Eocene
Cypress Plain	Cypress Hills, Swan Hills	Cypress Hills Formation, upper portion of Swan Hills deposits		early Oligocene to early Miocene
Flaxville Plain (No. 1 Bench)	Hand Hills, Wood Mountain, Willow Bunch Lake upland	Hand Hills Formation, Wood Mountain Formation, Willow Bunch Lake gravel		middle Miocene
	Flaxville upland, Mokowan Butte, Del Bonita upland (upper)	Flaxville Formation, upper Del Bonita gravel		late Miocene to early Pliocene
	Wintering Hills, Hand Hills Lake upland, Del Bonita upland (lower)	Wintering Hills gravel, Hand Hills Lake gravel, lower Del Bonita gravel		late Pliocene to early Pleistocene (tentative)
preglacial plains surface (No. 2 and No. 3 Benches)	modern plains surface and buried paleovalleys	Empress Group (Saskatchewan Gravel included as a formation)	tills of four separate montane and six separate continental glaciations	late Pliocene to Pleistocene
modern base level	modern major river valleys	modern alluvium		Holocene

Alberta, Mokowan Butte, and Cloudy Ridge (Figure 3); and (4) the lowermost continental till found in incised valleys and assumed to have deposited shield erratics high on the mountain front.

As noted in Section 2.1.1, previous workers had attributed the significant elevation difference between the remnant interfluves along the mountain front and the incised valleys of the No. 3 Bench (approximately 300–500 m near Mokowan Butte; Horberg, 1954) to a significant period of incision. In addition, they regarded the lithification and high degree of weathering and dissection of the Kennedy drift as indicative of its greater age relative to the sediments overlying the No. 3 Bench. However, Stalker and Harrison (1977) dismissed these observations and correlated the Kennedy drift with the limestone-bearing uppermost portion of the Saskatchewan gravels and overlying montane till within incised valleys. To explain how the same till could be deposited on surfaces that are separated in elevation by approximately 300 to 500 m, Stalker and Harrison (1977) described a mechanism that involved a thick montane piedmont at the mountain front with glacial tongues extending down major incised valleys.

All subsequent glaciations were less extensive, although they all reached south-central Alberta. Stalker (1977) reinterpreted the Lethbridge end moraine and the uppermost till sheet to the northeast of that feature as the least extensive continental glaciation, which he assigned to the late Wisconsinan. In total, up to six separate continental glaciations and four separate montane glaciations, some including re-advances, were inferred (Figure 5; Stalker and Harrison, 1977; Stalker, 1983). It is noteworthy that the number of Illinoian- to Wisconsinan-aged continental glaciations inferred in southern Alberta exceeded that recognized in the mid-continent (Stalker and Harrison, 1977).

Wagner (1966) suggested a less complicated Quaternary stratigraphy based on descriptions of the glacial stratigraphy west and south of Lethbridge. He critically evaluated previous stratigraphies developed in the area, especially those provided by Horberg (1952, 1954) and Stalker (1963), and derived interpretations that were broadly similar to those developed prior to 1955, albeit with several important modifications.

Wagner (1966) placed the Saskatchewan gravels at the base of the Quaternary stratigraphy and attributed the deposits to a number of cycles of uplift, incision, and planation where younger fluvial surfaces are topographically lower than older ones. Like Calhoun (1906), Alden (1932), and Horberg (1954), Wagner suggested that these cycles continued into the late Pleistocene. Importantly, this interpretation recognizes the stratigraphic significance of the physiographic bench architecture outlined by Alden (1932) and allows significant time separation between the Kennedy drift on the Flaxville surface and No. 2 Bench and glaciogenic deposits within incised valleys at much lower elevation. Consequently, Wagner suggested that the Kennedy drift is Illinoian or older.

Wagner (1966) suggested that all montane lateral moraines along the incised valleys of the mountain front are late Wisconsinan in age and not older as proposed by Horberg (1954). Moreover, Wagner noted that late Wisconsinan montane till near the mountain front is overlapped by late Wisconsinan continental till. To the north and east of the Lethbridge end moraine (c.f., Horberg, 1952, 1954), the continental till is overlain by a second, and thus younger, continental till that Wagner attributed to a late-glacial re-advance of continental ice.

Although Wagner (1966) described several of the same sections as Stalker (1963), including the important Brockett section (Figure 3), his stratigraphy is markedly different. Wagner defended his interpretation by noting that (1) at the Brockett section, soils or weathering profiles indicative of the passage of significant time between units are missing, and all units can be explained by a single late Wisconsinan continental advance with a fluctuating ice margin, and (2) Stalker (1963) separated tills (and correspondingly, glaciations) by physical characteristics of the tills themselves and "breaks" between them that, when observed in long, well-exposed sections, are not laterally continuous. Wagner suggested that till characteristics change laterally and "breaks" can disappear altogether.

Despite resembling the current understanding of the glacial stratigraphy of the region (c.f., Jackson et al., 2008), Wagner's work initially received little attention. Instead, regional correlations of the glacial stratigraphy of the western Interior Plains (Stalker, 1976; Fenton, 1984; Fulton et al., 1984) continued to adopt the stratigraphy primarily developed by Stalker insofar that the Saskatchewan gravels were conceptualized as underlying the first, most extensive till sheets and not necessarily being confined to incised valleys.

The Saskatchewan gravels unit was therefore considered an important stratigraphic marker that separated preglacial incision and planation from subsequent glacial geological processes. To reflect its correlative significance, Westgate (1965) and Whitaker and Christiansen (1972) attempted to define the deposit as a lithostratigraphic unit, and Stalker (1968) outlined criteria by which to identify and differentiate it from other fluvial or glaciofluvial deposits on the plains.

The most succinct and versatile definition was provided by Whitaker and Christiansen (1972), who based their work on the deposit near Empress, Alberta (Figure 3). Whitaker and Christiansen's definition conforms to the Code of Stratigraphic Nomenclature of 1961 (American Commission on Stratigraphic Nomenclature, 1961), which stipulates that the definition of a mappable unit is based on lithology and is independent of age or inferred geological history. Whitaker and Christiansen's definition is at the group rank and includes a lower, fluvial, gravel-dominated unit and an upper, proglacial lacustrine unit. The most important lithological constraints in the definition are that the deposit is stratified, that the lower unit is free of material derived from the Canadian Shield, and that it must overlie bedrock and underlie continental till. To avoid potential confusion that could be associated with the numerous name variations of Saskatchewan gravels already in the literature, Whittaker and Christiansen named the entire deposit the Empress Group. However, because its usage was entrenched in the literature, they recommended to retain the name "Saskatchewan Gravel or a variation therefrom" as a formal designation to define the lower, gravel-dominated, fluvial unit.

Whitaker and Christiansen (1972) noted that the Empress Group does not include upland Tertiary gravel formations such as the Cypress Hills Formation, Wood Mountain Formation, or the Flaxville Formation and is mainly restricted to deposits within preglacial valleys. However, being a lithostratigraphic definition, the Empress Group could include stratified deposits in a range of topographic settings, including on the surface of the No. 2 and No. 3 benches (Figure 5). Whitaker and Christiansen noted that potentially, the age of the deposit ranges from late Tertiary to Quaternary. Although this application of the definition is correct, it does not consider the stratigraphic significance of the physiographic bench architecture outlined by Alden (1932). Ultimately, redefinition of the Saskatchewan gravels as part of the Empress Group did little to resolve the stratigraphic ambiguity of the deposit outlined by Horberg (1954).

Investigation of upland planation surfaces and associated gravel deposits was continued in this period by Vonhof (1969) and Storer (1978). Vonhof outlined a stratigraphy of the deposits mantling the Cypress Hills, Swan Hills, Swift Current Creek Plateau, Flaxville uplands, Hand Hills, Hand Hills Lake upland, Wintering Hills, Del Bonita upland, Wood Mountain upland, and Willow Bunch Lake upland (Figure 3) and developed a model of the physiographic evolution of the plains. Storer refined the paleontology of the gravel deposits and thus improved the dating of the deposits in which fossils had been recovered. Where fossils had not been recovered, Vonhof made tentative age assignments based on comparisons of the relative elevation of deposits. In making such age assignments, Vonhof assumed that the amount of post-depositional regional uplift affecting each deposit was similar. In summary:

- The oldest deposits are the upper Eocene Swift Current Creek Beds, which mantle the Swift Current Creek Plateau. The stratigraphic assignment is based on fossil evidence. Potentially a lower portion of the Swan Hills deposit is also Eocene, but no fossils have been recovered there. At the Swift Current Creek Plateau, and potentially at the Swan Hills, the upper Eocene deposit grades into an overlying lower Oligocene to lower Miocene deposit (the Cypress Hills Formation in the case of the Swift Current Creek Beds), suggesting continued aggradation following initial incision of the paleovalley.
- The topographically highest deposits on the Interior Plains mantle the Cypress Hills and Swan Hills (upper portion). These deposits are lower Oligocene to lower Miocene based on fossil evidence recovered at Cypress Hills. Fossils have not been recovered from the Swan Hills deposit, but it is associated with the Cypress Hills deposit based on relative elevation.
- The next-highest deposits on the Interior Plains are the Hand Hills Formation (Stalker, 1973), Wood Mountain Formation, and Willow Bunch Lake deposits. These are assigned to the middle Miocene based on fossil evidence. Vonhof noted that the Wood Mountain Formation and Willow Bunch Lake deposits are topographically slightly higher than the adjacent Flaxville Formation in Montana, which was previously assigned to the upper Miocene to lower Pliocene based on fossil evidence.
- The Wintering Hills and Hand Hills Lake upland deposits are undated; however, these uplands are approximately 60 m lower than the Hand Hills and thus are presumed to be younger following the general observation (notwithstanding the Swift Current Creek Plateau deposits) that lower planation surfaces of the plains are younger than higher ones. The Wintering Hills and Hand Hills Lake upland deposits are postulated to be between upper Pliocene and lower Pleistocene.

- The Del Bonita upland area consists of an upper and a lower surface (Vonhof, 1969). No fossils have been recovered from gravel deposits mantling either surface; however, the upper deposit was associated with the Flaxville Plain by Alden (1932), and thus it is interpreted as upper Miocene to lower Pliocene. Therefore, Vonhof postulates that the lower deposit is Pliocene to possibly early Pleistocene in age.

Based on lithology, heavy mineral assemblages, gradients of the lower contact, and paleoflow measurements, Vonhof (1969) differentiated four groups of deposits and their potential source areas in the mountains. From north to south, these groups of deposits occurred across the Swan Hills; Hand and Wintering hills, and the Hand Hills Lake upland; the Del Bonita upland; and the Cypress Hills, Swift Current Creek Plateau, Wood Mountain, Willow Bunch Lake upland, and Flaxville upland. The geology and physiography of these remnant fluvial deposits indicate that the mountain headwaters of the major river systems responsible for their evolution remained essentially the same throughout the Tertiary. Modern major rivers that are associated with each of these groups are, respectively, the Athabasca River; the North Saskatchewan, Red Deer, and Bow rivers; the Old Man and Milk rivers; and the Missouri River. However, on the plains, significant lateral migration and incision evidently occurred. Vonhof (1969) interpreted a general southward lateral migration that potentially indicates that regional uplift was accompanied by tilting towards the south.

Vonhof (1969) summarized the geological history of the Interior Plains as follows (Table 2 and Figure 5):

- The major Tertiary drainage systems of the plains were established following the culmination of the Laramide Orogeny in the Eocene.[13]
- The only remnant Eocene deposits include those infilling a paleovalley below the Swift Current Creek Plateau and potentially a lower portion of the deposits capping the Swan Hills.
- During the late Eocene and Oligocene, fluvial aggradation and lateral planation formed the broad Cypress Plain, now represented by the Cypress Hills and Swan Hills.
- Incision and erosion of the Cypress Plain by lateral planation was initiated by renewed regional uplift in the early Miocene.
- The remainder of the Tertiary (Miocene and Pliocene) is characterized by intermittent uplift, incision, and planation, with minor aggradation that is recognized by progressively younger remnant fluvial planation surfaces and associated deposits distributed across the plains at successively lower elevations.

Vonhof (1969) acknowledged that this reconstruction was speculative, being based largely on inference since post-Laramide erosion of the Interior Plains removed much of the stratigraphic record associated with the Tertiary period. In addition, a lack of fossil recovery from many of the deposits makes age assignment difficult. Nonetheless, Vonhof provided a geological model for a time period about which relatively little was known.

13 Vonhof (1969) referenced Russell (1952) in assigning the culmination of the Laramide Orogeny to the Eocene. However, in a recent review, Osborn et al. (2006) concluded that no age was universally accepted for this event. Osborn et al. (2006) note that an age range of between 60 to 55 Ma (latest Paleocene) encompasses most estimates. Pana and van der Pluijm (2014) established radiometric dates on fault gauge across the Rocky Mountains in Canada that showed four phases of orogenic activity dated to the late Jurassic, middle Cretaceous, late Cretaceous, and early Eocene.

2.2.2 Summary

Between 1955 and 1985, the post-Laramide stratigraphic framework of the SSRB, and more broadly the plains, was commonly divided into nonglacial and glacial intervals. This division was predicated on the assumption that physiographic development of the plains—through cycles of tectonic uplift, fluvial incision, and planation—ceased prior to the first continental glaciation, and that stratigraphic development proceeded sequentially from nonglacial to glacial. Under this conceptualization, the nonglacial and glacial stratigraphies were not integrated and could not provide geometric and relative chronological references for one another.

An important consequence of the post-Laramide stratigraphic framework of this period was that the stratigraphic significance of the physiographic bench architecture (Alden, 1932) for deposits on the No. 2 and No. 3 benches was lost. Although the stratigraphy of upland deposits was refined (Vonhof, 1969), preglacial deposits at plains level and within buried incised valleys below the plains were amalgamated within a single lithostratigraphic unit termed the Empress Group.

2.3 Current Framework (1985 to present)

Jackson et al. (2008) noted that the current (post-1985) conceptualization of the post-Laramide stratigraphy has benefited from improvements in sedimentological research, absolute dating methods, and refined analytical techniques such as facies models (Walker, 1979) and lithostratigraphic analysis methods (Eyles et al., 1983; Miall, 1984, 1985). All have contributed to reduce the possibility that a regional stratigraphy could be biased by observations at only a few sections.

Since 1985, new sedimentological interpretations of both continental and montane glaciation have demonstrated that the previously published glacial stratigraphy of the region was untenable. Correspondingly, stratigraphic interpretations of the Saskatchewan Gravel Formation of the Empress Group as a regional preglacial deposit were rejected. Most researchers conceded that the bedrock surface did not represent the preglacial land surface, and much modification of the landscape must have occurred during interglacials and interstadials (Evans and Campbell, 1995).

In the latter part of this period, a new integrated regional stratigraphic framework was developed in which the nonglacial and glacial stratigraphies provided geometric and chronological references for one another. Furthermore, in some cases, stratigraphic interpretations were supported by modern analytical techniques and dating methods that were not available in previous periods. Remarkably, the regional stratigraphy from this period has much in common with the stratigraphy developed prior to 1955.

2.3.1 Stratigraphic Framework

Since 1985, the literature largely addresses specific themes which include glacial, preglacial, and nonglacial stratigraphy. Glacial stratigraphy includes studies of the deposits and features of continental and montane glaciations. Preglacial stratigraphy includes studies of the Empress Group. Nonglacial stratigraphy includes studies of the older, higher upland nonglacial deposits. In the latter part of this period, renewed presentations of an integrated regional post-Laramide stratigraphy are made. The stratigraphy defined since 1985 is summarized below (Table 3 and Figure 6).

2.3.1.1 Glacial Stratigraphy

The glacial stratigraphy of the SSRB is now considered the product of two continental glaciations (Proudfoot, 1985; Jackson et al., 2011) and as many as eight montane glaciations (Cioppa et al., 1995; Jackson et al., 2008). Importantly, continental glacial events are, for the most part restricted to the late

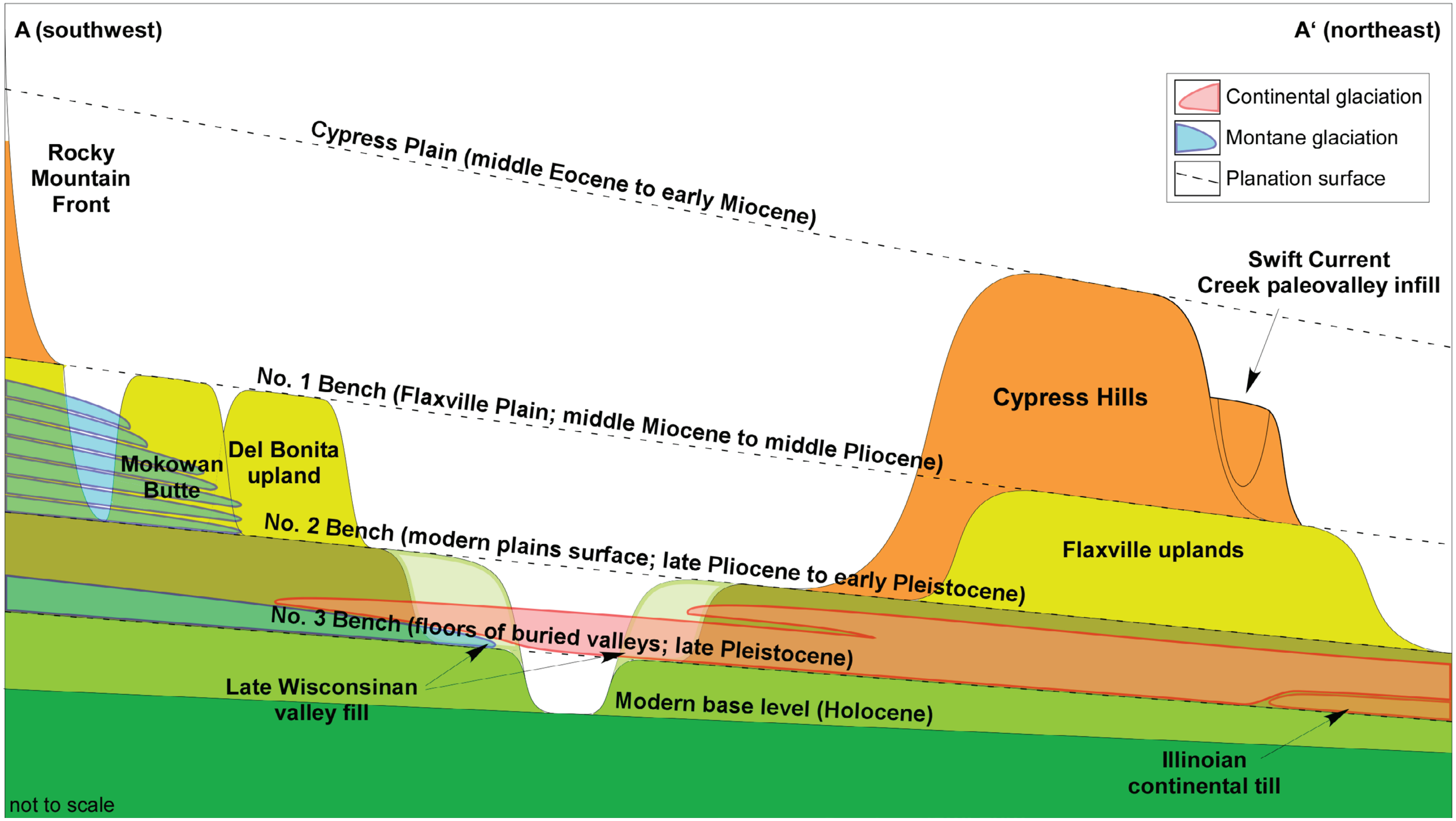

Figure 6. Diagrammatic cross-section A–A′ (Figure 3) showing major elements of the stratigraphic framework from the period 1985 to present.

Table 3. Current stratigraphic framework, 1985 to present.

Surface	Features / Localities	Nonglacial Deposits	Glacial Deposits	Age
Swift Current Creek paleovalley	Swift Current Creek Plateau, Swan Hills	Cypress Hills Formation, lower part of Swan Hills deposits		middle Eocene to early Miocene
Cypress Plain	Cypress Hills, Swan Hills, upper Del Bonita upland	Cypress Hills Formation, upper part of Swan Hills deposits, upper Del Bonita gravel		
Flaxville Plain (No. 1 Bench)	Wood Mountain	Wood Mountain Formation		middle Miocene
	Flaxville upland, Mokowan Butte, Hand Hills, Hand Hills Lake upland, Wintering Hills, lower Del Bonita upland	Flaxville Formation, Hand Hills Formation, Hand Hills Lake gravel, Wintering Hills gravel, lower Del Bonita gravel		late Miocene to middle Pliocene
No. 2 Bench	modern plains surface	Empress Group (Saskatchewan Gravel included as a formation)	up to seven montane tills (extend onto No. 1 Bench)	established by late Pliocene to early Pleistocene
No. 3 Bench	buried paleovalleys (within continental glacial limits)	Empress Group (Saskatchewan Gravel included as a formation)	late Wisconsinan montane till, Illinoian and late Wisconsinan continental till	established by late Pleistocene
modern base level	modern major river valleys	modern alluvium		Holocene

Pleistocene, and the most extensive continental glaciation in west-central to southwestern Alberta is considered to be late Wisconsinan (Young et al., 1994; Jackson et al., 2008, 2011). Collectively over the plains, a regional continental glacial stratigraphy emerged in this period that includes successively more extensive continental glaciations (Barendregt and Irving, 1998; Barendregt et al., 2012).

Based on stratigraphic work in central Alberta, Catto (1984) outlined significant problems with earlier reconstructions of the continental glacial stratigraphy of southwestern Alberta. Catto obtained mid-Wisconsinan radiocarbon dates on Empress Group sediments in the Edmonton area and observed that the deposit was overlain by a single late Wisconsinan continental till. He reasoned that areas to the south and west of Edmonton must also have been glaciated by continental ice during only the late Wisconsinan, because Edmonton is lower in elevation and is nearer the Keewatin ice centre of the continental ice sheet (Dyke and Prest, 1987). The implication of Catto's argument was that the glacial stratigraphy of southwestern Alberta established between 1955 and 1985, including up to six continental glaciations, was fundamentally incorrect.

Subsequently, in areas of Alberta to the north and east of its southwestern portion where the glacial stratigraphy of the period 1955–1985 had been developed, stratigraphic studies generally documented fewer, younger continental glaciations (Jennings, 1984; Proudfoot, 1985; Andriashek, 1988; Andriashek and Fenton, 1989; Liverman, 1989; Liverman et al., 1989; Evans and Campbell, 1992; Young et al., 1994; Kulig, 1995, 1996; Young et al., 1999). Jackson et al. (2011) observe that only the late Wisconsinan continental ice sheet extended south and west of a broad arc approximately defined by Watino, Edmonton, and Taber, Alberta (Figure 3). This observation supports the regional stratigraphy of the Interior Plains (c.f., Barendregt and Irving, 1988; Barendregt et al., 2012).

Importantly, within southwestern Alberta where the established glacial stratigraphy from the period 1955–1985 had been developed, significant elements of the continental glacial stratigraphy were reinterpreted. Vreeken (1989) established a deglacial chronology of southern Alberta based on sequences of glacial lakes and recessional moraines. He concluded that the Lethbridge end moraine (Figure 3) was deglaciated shortly before 11 200 B.P. and that this moraine marked a re-advance position (c.f., Horberg, 1954) and not the limit of late Wisconsinan continental ice (c.f., Stalker, 1977). Jackson et al. (1997) obtained cosmogenic ^{36}Cl dates on boulders from the southern portion of the foothills erratics train that support late Wisconsinan coalescence between montane and continental ice. Jackson et al. (1999) obtained cosmogenic ^{36}Cl dates on erratics at the all-time continental glacial limit in the foothills of southwestern Alberta confirming that the late Wisconsinan continental glaciation was the most extensive in this region. Jackson et al. (1999) stratigraphically linked the maximum continental limit with the oldest continental till known in the subsurface of southwestern Alberta, dating it as late Wisconsinan as well.

The montane glacial stratigraphy of southwestern Alberta was also significantly revised after 1985. Based on paleosol analysis and magnetostratigraphy, Karlstrom (1981, 1987, 1988, 2000) Barendregt et al. (1991), and Cioppa et al. (1995) outlined a montane glacial stratigraphy that includes up to seven glacial-interglacial cycles within the Kennedy drift, which is found on interfluves along the mountain front including Mokowan Butte and Cloudy Ridge (Figure 3). The cycles range between late Pliocene and early Illinoian. In mountain front valleys incised below the Kennedy drift, only one montane till has been recognized (Wagner, 1966; Jackson et al., 2008). It is late Wisconsinan based on relative stratigraphic position and extends onto the plains along buried mid-Wisconsinan paleovalleys approximately as far east as Lethbridge (Jackson et al., 2008). This montane till is overlapped by proglacial lacustrine sediment and late Wisconsinan continental till, indicating that montane glaciers were receding prior to the maximum continental advance (Jackson et al., 2008). A portion of the Saskatchewan Gravel within buried mid-Wisconsinan valleys likely represents late Wisconsinan montane outwash associated with this incursion of montane ice onto the plains (Jackson et al., 2008).

Based on further work in the foothills of southwestern Alberta, Jackson et al. (2008) proposed additional revision to the stratigraphy of southwest Alberta, which built on the integrated stratigraphy of the region initially proposed by Horberg (1954) and Wagner (1966). The stratigraphy is summarized as follows:

- Carbonate-bearing gravel outwash from the last major montane glacial advance onto the plains overlies the floors of buried valleys. This deposit is locally overlain by glaciolacustrine sediments associated with formation of proglacial lakes in tributary valleys dammed either by montane ice or outwash accumulation.
- Montane till overlies the basal gravel and outwash and is found within buried valleys. The till was deposited by montane piedmont glaciers that subsumed summits in the foothills up to 1600 m asl and extended out onto the plains as far east as Lethbridge. Jackson et al. (2008) described evidence for similar advances of piedmont glaciers north of the Porcupine Hills (Figure 3) but were unable to determine their easternmost extent. The montane till is locally overlain by gravel deposited upon retreat of the montane piedmont glacier or by glaciolacustrine sediments deposited in lakes that were dammed as the continental ice sheet advanced up the regional slope and into the study area.
- Continental till deposited during the most extensive advance of continental ice in southwestern Alberta overlies the montane till, glaciofluvial, and lacustrine deposits. This maximum continental ice advance reached the mountain front where it was blocked from entry into the mountains by montane valley glaciers.

- South of the Porcupine Hills and near the mountain front, continental till is overlain by montane till that represents a subsequent re-advance of montane glaciers. Farther east, continental till is overlain by glaciolacustrine sediments and a second continental till that represents a subsequent re-advance of the continental ice sheet. North of the Porcupine Hills, neither the montane nor the continental re-advance is recognized. During the continental re-advance, which coalesced with montane piedmont lobes, the foothills erratics train was transported along the suture between the two ice masses.
- The final retreat of continental ice from the foothills was characterized by the blockage of regional drainage by the receding ice margin and the accumulation of proglacial lakes, into which thick sequences of glaciolacustrine sediments were deposited. These lakes decanted across the Interior Plains as ice retreat opened progressively lower outlets. Other postglacial sediments are recognized, including glaciofluvial deposits, loess, and colluvium.

Jackson et al. (2008) concluded that all montane and continental glacial deposits below the montane tills on Mokowan Butte and Cloudy Ridge are late Wisconsinan.

Collectively, stratigraphic information obtained across central and southern Alberta indicates pre-late Wisconsinan continental glaciers did not extend into west-central or southwestern Alberta (Jackson et al., 2011). Pre-late Wisconsinan continental tills identified in the easternmost portion of the SSRB (Medicine Hat and Dinosaur Provincial Park) relate to an earlier glaciation that is tentatively assigned to the Illinoian (Barendregt and Irving 1998; Jackson et al., 2011).

2.3.1.2 Preglacial Stratigraphy

Preglacial stratigraphy includes studies of the Empress Group sediments that overlie lower planation surfaces, including the general modern plains surface and the floors of buried incised valleys (the No. 2 and No. 3 benches; Figure 3).[14] Although the lowermost fluvial unit within this group, the Saskatchewan Gravel Formation, had been considered to be a contiguous regional preglacial deposit (Stalker, 1963, 1968, 1969, 1976, 1983; Westgate, 1965; Whitaker and Christiansen, 1972; Stalker and Harrison, 1977) and was formally defined (Whitaker and Christiansen 1972), subsequent revisions of the continental glacial stratigraphy necessitated further consideration of the stratigraphic significance of this unit with respect to its age and genesis. The lithostratigraphic definition, however, being independent of age or inferred geological history of the deposit, remained intact.

The successive preglacial and interglacial drainage systems that existed on the Interior Plains would have been disrupted by ice damming, valley infill, and ice-marginal drainage diversion upon advance and retreat of each successively more extensive glaciation (Barendregt and Irving, 1998; Barendregt et al., 2012; Jackson et al., 2011). These events resulted in preglacial deposits that are successively younger westward across the plains (Evans and Campbell, 1995; Jackson et al. 2011; Cummings et al., 2012). Therefore, as noted by Evans and Campbell (1995), the Empress Group sediments may represent several valley fill and excavation events in addition to regional deposition of preglacial deposits. As a consequence of being recognized as a time-transgressive deposit, the Empress Group could no longer be used in stratigraphic studies as a regional time-stratigraphic marker.

14 In the literature, the Saskatchewan gravels are commonly described as preglacial because they lack clasts or minerals derived from the Canadian Shield (see note 8). However, based on the montane glacial stratigraphy outlined in the previous section, a portion of this formation likely contains montane glaciofluvial outwash and is only preglacial with respect to continental glaciation. The term preglacial is maintained in this report as it is entrenched in the literature.

Few finite dates have been obtained on the Empress Group sediments beyond the youngest mid-Wisconsinan deposits in west-central to southwestern Alberta (Catto, 1984; Liverman, 1989; Liverman et al., 1989; Young et al., 1994; Burns, 1996). However, several important observations provide limited age control. Based on a regional review of buried valley aquifers in the Interior Plains, Cummings et al. (2012) noted that the Empress Group sediments are younger than upland gravel formations dated to less than 5 Ma. Within incised buried valleys near Saskatoon, Barendregt et al. (2012) noted that the preglacial Empress Group includes magnetically normal and reversed sediments that span about 2.0 Ma between approximately 0.83 and 3.0 Ma. Interestingly, this age range overlaps the age range of early montane glacial events that deposited the Kennedy drift on Mokowan Butte and Cloudy Ridge (between approximately 0.78 and 2.6 Ma; Cioppa et al., 1995) near the mountain front outlined above.

2.3.1.3 Nonglacial Stratigraphy

The physiography of the Interior Plains had long been conceptualized as the product of fluvial incision and planation where the dissected remnants of older surfaces are topographically higher than younger, more complete surfaces. In this interval, however, comprehensive models of the physiographic development of the Interior Plains were developed. In addition, the stratigraphy of remnant deposits was better constrained in this interval based on detailed lithological analysis, paleoenvironmental reconstruction, assessment of depositional environments, and new dates including several radiometric tephra ages.

Edwards and Scafe (1994) provided a comprehensive evaluation of Tertiary and preglacial sand and gravel deposits in Alberta. The authors found that the four levels of planation surfaces previously identified in southern Alberta, southern Saskatchewan, and northern Montana (Alden, 1932) extended northwards across the entire province. Edwards and Scafe divided the gravel deposits that mantle these surfaces into seven stratigraphically independent lithological groups that relate to discrete source areas in the mountains. Groups are approximately superimposed on modern river basins as follows: Group 1 – South Saskatchewan River; Group 2 – Bow and Red Deer Rivers; Groups 3 and 4 – North Saskatchewan River; Group 5 – Athabasca River; Group 6 – Peace River; and Group 7 lies in the southeast corner of Alberta and is predominantly represented by the Cypress Hills deposit. The Cypress Hills deposit is not superimposed on a modern river basin but forms part of the modern continental drainage divide.

Edwards and Scafe (1994) provided a geological history of the western plains following the end of the Laramide Orogeny in the early Eocene (Pana and van der Pluijm, 2014). Immediately following orogeny, erosion dominated, as evidenced by the fact that Eocene deposits are largely missing from Alberta's rock record and are found only in deep paleovalleys (lower part of Cypress Hills Formation and Swan Hills deposits). Continental uplift and erosion continued until the late Pleistocene; however, these processes were punctuated by four periods that are represented by four levels of fluvial planation and deposition. In total, more than 1000 m of sediment has been removed from the modern plains surface (Nurkowski, 1984). Correlation of gravel capped uplands in the SSRB with fluvial planation surfaces as per Edwards and Scafe (1994) is summarized in Table 3 below.

A comprehensive tectonic model of the physiographic development of the entire Interior Plains was developed by Leckie (2006). The model was based upon the deposits of the paleo–Missouri River that, prior to diversion to the Gulf of Mexico, was the primary drainage system of the Interior Plains, which flowed to Hudson Bay. Deposits of this system include Cypress Hills Formation (Swift Current Creek Plateau and Cypress Hills; Figure 3), Wood Mountain Formation (Wood Mountain; Figure 3), Flaxville Formation (Flaxville upland; Figure 3), and Souris River gravel (localized occurrences within buried valleys in southwestern Manitoba). Each of these, respectively, is successively younger, lower, and farther east.

Leckie (2006) interpreted the punctuated, easterly-migration of the paleo–Missouri River as the product of tectonic events that began following the culmination of the Laramide Orogeny (early Eocene; Pana and van der Pluijm, 2014), after which, transpressional tectonics and associated basin filling ceased and a subsequent phase of transtensional tectonics, including differential uplift accompanied by magmatism, began. Following a near-final phase of fill in the foreland basin represented by the nonmarine Paleocene Ravenscrag Formation (approximately equivalent to the upper Willow Creek and lower Porcupine Hills formations in southwestern Alberta and the upper Scollard and lower Paskapoo formations in central Alberta), the basin was uplifted. Deep valleys, represented today by the Swift Current Creek paleovalley, were incised through the basin and subsequently infilled by Eocene deposits. The Cypress Plain developed above the Swift Current Creek paleovalley across a basin-wide unconformity upon which up to 180 m of sediment was removed in southern Alberta (Nurkowski, 1984). Deposition, or at least reworking, of the Cypress Hills Formation continued until early Miocene time. With continued differential uplift, the north-to-northeast-flowing fluvial system shifted east to erode a planation surface represented by Wood Mountain and the overlying middle Miocene Wood Mountain Formation. A subsequent cycle of uplift, valley incision with terrace redevelopment and deposition produced the upper Miocene to middle Pliocene Flaxville Formation. Finally, following another cycle of uplift, valley incision, and deposition, the easternmost of the deposits, the Souris River gravel, was deposited in preglacial valleys. These valleys likely remained active during one or more Pleistocene glaciations as Shield clasts are found in the gravels.

All deposits of the paleo–Missouri River observed by Leckie (2006) share lithological similarities that indicate ultimate derivation from the pre-intrusive, widely distributed Eocene Wasatch Formation (Leckie, 2006), of which the nearest outcrops to the SSRB occur in central to north-central Montana (Constenius, 1996). In addition, average paleoflow measurements in all deposits are north to northeast. In contrast to the reconstruction of Vonhof (1969), in which a southward migration of the paleo–Missouri River was proposed, Leckie (2006) proposed an eastward migration that did not recycle significant amounts of gravel. Eastward migration of the paleo–Missouri River fits the provenance and paleoflow observations better than southward migration. In addition, eastward migration provides a better geometric fit with differential uplift of mountains and plains and intrusive uplift in Montana (Leckie, 2006) south of the deposits investigated by both Vonhof and Leckie.

Leckie (2006) noted that in response to regional uplift between the Oligocene and late Miocene, the continental drainage divide between Hudson Bay and the Gulf of Mexico migrated approximately 600 to 800 km north to its current location across the Milk River Ridge and the Cypress Hills (Figure 1). East of the Cypress Hills, the remaining portion of Hudson Bay drainage that successively deposited the Wood Mountain Formation, Flaxville Formation, and Souris River gravel was finally diverted to the Gulf of Mexico via the Missouri River by continental glaciation in the Pleistocene (Leckie, 2006).

The rate of physiographic evolution of the Interior Plains is partially constrained by tephra dates (Vreeken and Westgate, 1992) and paleomagnetic correlation (Barendregt et al., 1997) from a single loess deposit, the Davis Creek silt, which mantles the east block of the Cypress Hills and four lower, nested erosion surfaces. The lower surfaces are down-cut in the south side of the monadnock and include (from upper to lower) the Murraydale, the Fairwell, the Moirvale, and the Sucker surfaces. The Fairwell surface is correlated to the Flaxville Plain. A fission track age of 8.3 Ma established on the tephra within the silt indicates that much of the topographic relief of the Cypress Hills below the Flaxville Plain was already developed by the late Miocene. The Flaxville Plain remained active elsewhere until the mid-Pliocene; however, later fluvial activity was likely restricted to lower terraces (Leckie, 2006).

2.3.2 Summary

The current conceptualization of the post-Laramide stratigraphic framework of the SSRB is the product of geological investigation and hypothesis testing and is underpinned by stratigraphic components that are spatially and temporally constrained. Importantly, the post-Laramide stratigraphy is once again conceptualized as an integrated product of glacial and nonglacial processes where each provides at least a partial chronological and geometric reference upon which to structure the other. The stratigraphic framework is summarized as follows (Table 3 and Figure 6):

- Following the Laramide Orogeny, transtensional tectonics accompanied by magmatism activated differential uplift across the basin (Leckie, 2006). Initially fluvial systems responded by incising paleovalleys which were subsequently infilled by Eocene deposits (Vonhof, 1969; Leckie, 2006). A broad fluvial planation surface called the Cypress Plain (Alden, 1932) developed across the basin between the Oligocene and early Miocene (Storer, 1978). The present-day Cypress Hills and Swan Hills monadnocks are the only remnants of this vast surface (Vonhof, 1969; Leckie, 2006).
- Incision of the foreland basin continued until at least the late Pleistocene. Within this period, additional planation surfaces were cut below the Cypress Plain. These additional surfaces are dissected and their erosional remnants are widely distributed. Without comprehensive dating control, correlation between these remnants is tenuous. However, three groups of remnant surfaces of similar age and elevation have been recognized within, and proximal to southern Alberta. These are: the Flaxville Plain (No. 1 Bench; Alden,1932) which, including Wood Mountain, is assigned to the middle Miocene to mid-Pliocene (Leckie, 2006); a surface at or slightly above the modern plains called the No. 2 Bench (Alden, 1932), which was assigned to the late Pliocene to early Pleistocene (Edwards and Scafe, 1994); and a surface incised below the general level of the modern plains called the No. 3 Bench (Alden,1932), which was assigned to the late Pleistocene in southern Alberta (Evans and Campbell, 1995; Jackson et al., 2011; Cummings et al., 2012).
- Differential uplift tilted the foreland basin, shifting the continental drainage divide northward and major paleodrainage systems eastward by hundreds of kilometres (Leckie, 2006). For all paleodrainage systems recognized in Alberta, the mountain headwaters have remained nearly fixed as fluvial deposit lithologies, irrespective of age, broadly correspond with mountain source area lithologies (Edwards and Scafe, 1994).
- Interfluves adjacent to the mountain front are overlain by up to seven montane tills, which, based on weathered profiles and paleomagnetic investigation, range between the Pliocene and Illinoian (Cioppa et al. 1995; Karlstrom, 2000). Consequently, it would appear that these montane glaciations extended onto the No. 2 Bench prior to overwhelming the adjacent higher surface of the Flaxville Plain. Montane glaciation subsequent to the Illinoian event and prior to late Wisconsinan glaciation that deposited till on the No. 3 Bench within deeply incised valleys of the mountain front has not been identified (Jackson et al., 2008).
- By the mid-Wisconsinan, the late Pleistocene planation surface (No. 3 Bench) was established as an incised drainage system. Between the mountain front and a broad arc approximately defined by Medicine Hat, Edmonton, and Watino, the floor of the late Pleistocene planation surface is overlain by mature quartzitic basal gravel derived exclusively from the mountains, indicating that the area had not been previously glaciated by continental ice.
- Continental glaciation appears to conform to the Barendregt-Irving hypothesis, which postulates that successive continental glaciations were more extensive in a southwestward direction across the plains (Barendregt and Irving, 1988). At Medicine Hat and Dinosaur Provincial Park near the southern Alberta-Saskatchewan border, two separate continental glaciations have been recorded by Proudfoot (1985) and Evans and Campbell (1995), respectively. The oldest of these is assessed as Illinoian. However, late Wisconsinan continental glaciation extended farther south and west, reaching the

foothills and extending into western Montana (Jackson et al., 2008). Therefore, much of the SSRB west of Medicine Hat was glaciated by continental ice only once, during the late Wisconsinan.

- As continental ice sheets expanded across the plains towards the southwest from ice divides near Hudson Bay, they advanced against the regional slope and dammed drainage within the incised valleys of the late Pleistocene planation surface (No. 3 Bench) to form proglacial lakes. Infilling of the preglacial drainage network with proglacial and glacial sediment or blocking and diversion of the drainage system by continental ice would have extended farther to the southwest with each successively more extensive continental glaciation. As such, shield-clast-free gravel along the floors of the No. 3 Bench, and possibly the No. 2 Bench, necessarily contains unconformities and becomes younger to the southwest.

3 Discussion

Geological studies since 1985 have made use of new analytical techniques and subsurface data to develop an integrated stratigraphy of southern Alberta that largely supports the stratigraphic framework originally proposed by Alden (1932) and Horberg (1954).

The accomplishment of the early studies was that they were based on regional syntheses that did not subdivide glacial and nonglacial processes. Instead, the post-Laramide stratigraphy was seen as the product of nearly continuous tectonic-fluvial processes that were punctuated by glacial events. The landscape itself, with its series of nested planation surfaces between older remnant uplands and younger incised valleys, represents an inverted stratigraphic column by which the relative age of the nonglacial and glacial deposits that mantled the surfaces could be assessed. The distribution and age determinations of glacial deposits complemented the nonglacial stratigraphy such that both stratigraphies were integrated in a single post-Laramide stratigraphic framework for the region.

In contrast, workers from the subsequent period (1955–1985) considered the tectonic-fluvial development of the plains to have been completed prior to the first glaciations. Therefore, the stratigraphic significance of the physiographic bench architecture described by Alden (1932) could not be used to underpin the glacial stratigraphy or vice versa. As a consequence, the glacial stratigraphy from this period is inconsistent with those of the preceding and following periods. Workers from this period were also hindered by the use of the site-specific type-section methodology, which is poorly suited to stratigraphic study of heterogeneous Quaternary sediments. For example, it is now apparent that stacked till sequences emplaced by glacial thrusting were misinterpreted as products of multiple glaciations within the SSRB.

The current (1985 to present) post-Laramide stratigraphic framework of the SSRB, and of the western Interior Plains in general, is fairly well constrained, and the tectonic-fluvial and glacial stratigraphies are largely integrated. However, the stratigraphic significance of the bench architecture outlined by Alden (1932) has not been recognized as completely as it was prior to 1955. Specifically, the No. 2 Bench remains largely unrecognized in the study area. Following Horberg (1954), Edwards and Scafe (1994) are the only authors who explicitly included the No. 2 Bench in the stratigraphic framework of the region. Fluvial deposits mantling both the No. 2 Bench and No. 3 Bench are typically included within the Empress Group (Whitaker and Christiansen, 1972; also see Figure 6 and Table 3), even though it is apparent that a significant unconformity, represented by uplift and incision of the No. 2 Bench, separates the two deposits.

Subsurface mapping in the SSRB has identified the extents of buried fluvial deposits within the incised valleys of the No. 3 Bench in southern Alberta (Meyboom, 1961; Farvolden et al., 1963; Geiger, 1965, 1968; Toth et al., 1977; Lemay and Guha, 2009). Furthermore, Edwards and Scafe (1994) have outlined the known fluvial deposits that mantle the No. 2 Bench in Alberta. As such, it appears that both deposits could be distinctly mapped and thus could be defined as separate lithostratigraphic units. Notwithstanding the introduction of a new lithostratigraphic unit to define the fluvial deposits on the No. 2 Bench, stratigraphic studies in the SSRB would benefit from the qualification of Empress Group sediments based upon the bench on which they are situated.

Based on this literature review, it is anticipated that future stratigraphic studies in the SSRB, including 3-D modelling projects undertaken by the AGS, will be more successful if they recognize the stratigraphic significance of the physiographic bench architecture of the region (Alden, 1932) and consider the post-Laramide stratigraphic framework as an integrated product of nearly continuous tectonic-fluvial processes that were punctuated by glacial events.

4 Conclusion

The post-Laramide stratigraphy of the SSRB has been studied for more than a century. During this time it has been nearly continuously revised. Two revisions have been so fundamental that the literature reviewed in this report has been broken into three periods around the approximate dates of these revisions: 1955 and 1985. Remarkably, although technologies, methodologies, and topographic and subsurface data availability improved through all three periods, the current (1985 to present) well-constrained stratigraphy broadly resembles that proposed at the end of the first period (pre-1955). The accomplishment of these early workers was largely the result of conceptualization of the stratigraphic framework of the SSRB as an integrated product of tectonic-fluvial development punctuated by glaciation. In this stratigraphic framework, both the nonglacial and glacial stratigraphies provided relative chronological and geometric references for one another.

Future initiatives in the SSRB by the AGS will include 3-D hydrostratigraphic modelling efforts based on evaluation of subsurface data. The post-Laramide stratigraphic framework outlined in this report is intended to provide context for the assignment of hydrostratigraphic units and the delineation of geobodies in these models. These efforts will largely represent the first significantly new approach to stratigraphic investigation in the area as nearly all stratigraphic work reviewed in this document is based on surface and section observations. As such, it is anticipated that the physiographic bench architecture will be better recognized than it has been previously, especially for the No. 2 and No. 3 benches, which have been obscured by glaciation. In any stratigraphic or modelling study of the SSRB, it will be useful to consider an important theme from this review: that a stratigraphic approach in which the fluvial-tectonic and glacial stratigraphies are integrated has been shown to be successful in the SSRB beyond significant improvements in methodologies and data availability.

5 References

Agassiz, L. (1864): Ice Period in America; Atlantic Monthly, v. 14, p. 86–93.

Alden, W.C. (1929): Thomas Chrowder Chamberlin's contributions to glacial geology; The Journal of Geology, v. 37, no. 4, p. 293–319.

Alden, W.C. (1932): Physiography and glacial geology of eastern Montana and adjacent areas; U. S. Geological Survey, Professional Paper 174, 133 p.

American Commission on Stratigraphic Nomenclature (1961): Code of Stratigraphic Nomenclature; Bulletin of the American Association of Petroleum Geologists, v. 45, no. 5, p. 645–665.

Andriashek, L.D. (1988): Quaternary stratigraphy of the Edmonton map area, NTS 83H; Terrain Sciences Department, Natural Resources Division, Alberta Research Council, Open File Report 1988-04, 29 p., URL <http://ags.gov.ab.ca/publications/abstracts/OFR_1988_04.html> [June 2014].

Andriashek, L.D. and Fenton, M.M. (1989): Quaternary stratigraphy and surficial geology of the Sand River area 73L; Alberta Research Council, Bulletin 57, 154 p., URL <http://ags.gov.ab.ca/publications/abstracts/BUL_057.html> [June 2014].

Arnold, J.R. and Libby, W.F. (1949): Age determinations by radiocarbon content: checks with samples of known age; Science, v. 110, no. 2869, p. 678–680.

Barendregt, R.W. and Irving, E. (1998): Changes in the extent of North American ice sheets during the late Cenozoic; Canadian Journal of Earth Sciences, v. 35, no. 5, p. 504–509.

Barendregt, R.W., Irving, E. and Karlstrom, E.T. (1991): Paleomagnetism of Quaternary and late Tertiary sediments on Mokowan Butte, southwestern Alberta; Canadian Journal of Earth Sciences, v. 28, no. 12, p. 1956–1964.

Barendregt, R.W., Vreeken, W.J., Irving, E. and Baker, J. (1997): Stratigraphy and paleomagnetism of the late Miocene Davis Creek silt, east block of the Cypress Hills, Saskatchewan; Canadian Journal of Earth Sciences, v. 34, no. 10, p. 1325–1332.

Barendregt, R.W., Enkin, R.J. and Tessler, D.L. (2012): Magnetostratigraphy of late Neogene glacial, interglacial, and preglacial sediments in the Saskatoon and Regina areas, Saskatchewan, Canada; Studia Geophysica et Geodaetica, v. 56, no. 3, p. 705–724.

Beaty, C.B. (1975): The landscapes of southern Alberta: a regional geomorphology; University of Lethbridge, Lethbridge, Alberta, 95 p.

Bobrowsky, P. and Rutter, N.W. (1992): The Quaternary geological history of the Canadian Rocky Mountains; Géographie Physique et Quaternaire, v. 46, no. 1, p. 5–50.

Bostock, H.S. (1970): Physiographic Regions of Canada; Geological Survey of Canada, Map 1254A, scale 1:5 000 000.

Burns, J.A. (1996): Vertebrate paleontology and the alleged ice-free corridor: the meat of the matter; Quaternary International, v. 32, p. 107–112.

Calhoun, F.H.H. (1906): The Montana lobe of the Keewatin ice sheet; U. S. Geological Survey, Professional Paper 50, 62 p.

Catto, N.R. (1984): Glacigenic deposits at the Edmonton convention centre, Edmonton, Alberta; Canadian Journal of Earth Sciences, v. 21, no. 12, p. 1473–1482.

Chamberlin, T.C. (1896): Nomenclature of glacial formations; The Journal of Geology, v. 4, no. 7, p. 872–876.

Christiansen, E.A. (1959): Glacial geology of the Swift Current area, Saskatchewan; Saskatchewan Geological Survey, Report 32, 62 p.

Cioppa, M.T., Karlstrom, E.T., Irving, E. and Barendregt, R.W. (1995): Paleomagnetism of tills and associated paleosols in southwestern Alberta and northern Montana: evidence for late Pliocene-Early Pleistocene glaciations; Canadian Journal of Earth Sciences, v. 32, no. 5, p. 555–564.

Collier, A.J. and Thom, W.T. (1918): The Flaxville Gravel and its relation to other terrace gravels of the northern Great Plains; U. S. Geological Survey, Professional Paper 108, 5 p.

Constenius, K.N. (1996): Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt; Geological Society of America Bulletin, v. 108, no. 1, p. 20–39.

Cope, E.D. (1891): On vertebrata from the Tertiary and Cretaceous rocks of the Northwest Territory, Vol. I: The species from the Oligocene or lower Miocene beds of the Cypress Hills; Geological Survey of Canada, 25 p.

Cowie, J.W. and Bassett, M.G. (1989): International Union of Geological Sciences 1989 global stratigraphic chart with geochronometric and magnetostratigraphic calibration; Episodes, v. 12, no. 2, 1 sheet.

Cummings, D.I., Russell, H.A.J. and Sharpe, D.R. (2012): Buried-valley aquifers in the Canadian prairies: geology, hydrogeology, and origin; Canadian Journal of Earth Sciences, v. 49, no. 9, p. 987–1004.

Dawson, G.M. and McConnell, R.G. (1895): Glacial deposits of southwestern Alberta in the vicinity of the Rocky Mountains; Bulletin of the Geological Society of America, v. 7, p. 31–66.

Dyke, A.S. and Prest, V.K. (1987): Late Wisconsinan and Holocene history of the Laurentide Ice Sheet; Géographie Physique et Quaternaire, v. 61, no. 2, p. 237–263.

Dyke, A.S., Vincent, J.S., Andrews, J.T., Dredge, L.A., Cowan, W.R. and Richard, P.J.H. (1989): The Laurentide Ice Sheet and an introduction to the Quaternary geology of the Canadian Shield; in The Quaternary geology of Canada and Greenland, R.J. Fulton (ed.), Geological Survey of Canada, p. 175-318.

Edwards, D.W.A. and Scafe, D. (1994): Mapping and resource evaluation of the Tertiary and preglacial sand and gravel formations of Alberta; Alberta Geological Survey, Open File Report 1994-06, 246 p., URL <http://ags.gov.ab.ca/publications/abstracts/OFR_1994_06.html> [June 2014].

Evans, D.J.A. and Campbell, I.A. (1992): Glacial and postglacial stratigraphy of Dinosaur Provincial Park and surrounding plains, southern Alberta, Canada; Quaternary Science Reviews, v. 11, no. 5, p. 535–555.

Evans, D.J.A. and Campbell, I.A. (1995): Quaternary stratigraphy of the buried valleys of the lower Red Deer River, Alberta, Canada; Journal of Quaternary Science., v. 10, no. 2, p. 123–148.

Eyles, N., Eyles, C.H. and Miall, A.D. (1983): Lithofacies types and vertical profile models: an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences; Sedimentology, v. 30, no. 3, p. 393–410.

Farvolden, R.N., Menley, W.A., LeBreton, E.G., Lennox, D.H. and Meyboom, P. (1963): Early contributions to the groundwater hydrology of Alberta; Research Council of Alberta, Bulletin 012, 123 p., URL <http://ags.gov.ab.ca/publications/abstracts/BUL_012.html> [June 2014].

Fenton, M.M. (1984): Quaternary stratigraphy of the Canadian prairies; Geological Survey of Canada, Paper 84-10, p. 57–68.

Fulton, R.J. and Prest, V.K. (1987): The Laurentide Ice Sheet and its significance; Géographie Physique et Quaternaire, v. 41, no. 2, p. 181–186.

Fulton, R.J., Fenton, M.M. and Rutter, N.W. (1984): Summary of Quaternary stratigraphy and history, western Canada; Geological Survey of Canada, Paper 84-10, p. 69–83.

Geiger, K.W. (1965): Bedrock topography of southwestern Alberta; Research Council of Alberta, Earth Sciences Report 1965-01, 14 p.

Geiger, K.W. (1968): Bedrock topography of the Gleichen map-area, Alberta; Research Council of Alberta, Earth Sciences Report 1967-02, 14 p.

Head, M.J., Gibbard, P. and Salvador, A. (2008): The Tertiary: a proposal for its formal definition; Episodes, v. 31, p. 248-250.

Horberg, C.L. (1952): Pleistocene drift sheets in the Lethbridge region, Alberta, Canada; Geology, v. 60, no. 4, p. 303–330.

Horberg, C.L. (1954): Rocky Mountain and continental Pleistocene deposits in the Waterton region, Alberta, Canada; Geological Society of America Bulletin, v. 65, no. 11, p. 1093–1150.

Jackson, L.E., Jr., Phillips, F.M., Shimamura, K. and Little, E.C. (1997): Cosmogenic (super 36) Cl dating of the Foothills Erratics Train, Alberta, Canada; Geology, v. 25, no. 3, p. 195–198.

Jackson, L.E., Jr., Phillips, F.M. and Little, E.C. (1999): Cosmogenic (super 36) Cl dating of the maximum limit of the Laurentide Ice Sheet in southwestern Alberta; Canadian Journal of Earth Sciences, v. 36, no. 8, p. 1347–1356.

Jackson, L.E., Jr., Leboe, E.R., Little, E.C., Holme, P.J., Hicock, S.R., Shimamura, K. and Nelson, F.E.N. (2008): Quaternary stratigraphy and geology of the Rocky Mountain Foothills, southwestern Alberta; Geological Survey of Canada, Bulletin 583, 50 p.

Jackson, L.E., Jr., Andriashek, L.D. and Phillips, F.M. (2011): Limits of successive middle and late Pleistocene continental ice sheets, Interior Plains of southern and central Alberta and adjacent areas. in Quaternary glaciations: extent and chronology, J. Ehlers, P.L. Gibbard and P.D. Hughes. (ed.), Elsevier, Philadelphia, Pennsylvania, p. 575–589.

Jennings, D.B. (1984): The late Quaternary geomorphology of Elk Island National Park, central Alberta; M.Sc. thesis, University of Alberta, 197 p.

Johnston, W.A. (1933): Quaternary geology of North America in relation to migration of man; in The American aborigines: their origin and antiquity, D. Jennes. (ed.), University of Toronto Press, p. 9–45.

Karlstrom, E.T. (1981): Late Cenozoic soils of Glacier and Waterton parks area, northwestern Montana and southwestern Alberta, and paleoclimatic implications; Ph.D. thesis, University of Calgary, 358 p.

Karlstrom, E.T. (1987): Stratigraphy and genesis of five superposed paleosols in pre-Wisconsinan drift on Mokowan Butte, southwestern Alberta; Canadian Journal of Earth Sciences, v. 24, no. 11, p. 2235–2253.

Karlstrom, E.T. (1988): Multiple paleosols in pre-Wisconsinan drift, northwestern Montana and southwestern Alberta; Catena, v. 15, no. 2, p. 147–178.

Karlstrom, E.T. (2000): Fabric and origin of multiple diamictons within the pre-Illinoian Kennedy Drift east of Waterton-Glacier International Peace Park, Alberta, Canada, Montana, USA; Geological Society of America Bulletin, v. 112, no. 10, p. 1496–1506.

Knox, R.W.O'B., Pearson, P.N., Barry, T.L., Condon, D.J., Cope, J.C.W., Gale, A.S., Gibbard, P.L., Kerr, A.C., Hounslow, M.W., Powell, J.H., Rawson, P.F., Smith, A.G., Waters, C.N. and Zalasiewicz, J. (2012): Examining the case for the use of the Tertiary as a formal period of informal unit; Proceedings of the Geologists' Association, V. 123, p. 390-393.

Kulig, J.J. (1995): The Quaternary history of the Cypress Hills and adjacent areas in Alberta and Saskatchewan; Ph.D. thesis, University of Alberta, 319 p.

Kulig, J.J. (1996): The glaciation of the Cypress Hills of Alberta and Saskatchewan and its regional implications; Quaternary International, v. 32, p. 53–77.

Leckie, D.A. (2006): Tertiary fluvial gravels and evolution of the western Canadian prairie landscape; Sedimentary Geology, v. 190, p. 139–158.

Leckie, D.A. and Cheel, R.J. (1989): The Cypress Hills Formation (upper Eocene to Miocene): a semi-arid braidplain deposit resulting from intrusive uplift; Canadian Journal of Earth Sciences, v. 26, no. 10, p. 1918–1931.

Lemay, T.G. and Guha, S. (2009): Compilation of Alberta groundwater information from existing maps and data sources; Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-02, 43 p., URL <http://ags.gov.ab.ca/publications/abstracts/OFR_2009_02.html> [June 2014].

Liverman, D.G.E. (1989): The Quaternary geology of the Grande Prairie area, Alberta; Ph.D. thesis, University of Alberta, 360 p.

Liverman, D.G.E., Catto, N.R. and Rutter, N.W. (1989): Laurentide glaciation in west-central Alberta: a single (Late Wisconsinan) event; Canadian Journal of Earth Sciences, v. 26, no. 2, p. 266–274.

MacDonald, G.M., Beukens, R.P., Kieser, W.E. and Vitt, D.H. (1987): Comparative radiocarbon dating of terrestrial plant macrofossils and aquatic moss from the 'ice-free corridor' of western Canada; Geology, v. 15, no. 9, p. 837–840.

McConnell, R.G. (1885): Report on the Cypress Hills, Wood Mountain, and adjacent country; Geological Survey of Canada, Annual Report, 78 p.

Meyboom, P. (1961): Groundwater resources of the city of Calgary and vicinity; Research Council of Alberta, Bulletin 008, 72 p., URL <http://ags.gov.ab.ca/publications/abstracts/BUL_008.html> [June 2014].

Miall, A.D. (1984): Principles of sedimentary basin analysis; Springer-Verlag, New York, New York, 668 p.

Miall, A.D. (1985): Architectural-element analysis; a new method of facies analysis applied to fluvial deposits; Earth Science Reviews, v. 22, no. 4, p. 261–308.

Nurkowski, J.R. (1984): Coal quality, coal rank variation and its relation to reconstructed overburden, upper Cretaceous and Tertiary plains coals, Alberta, Canada; American Association of Petroleum Geologists Bulletin, v. 68, no. 3, p. 285–295.

Osborn, G., Stockmal, G. and Haspel, R. (2006): Emergence of the Canadian Rockies and adjacent plains: a comparison of physiography between end-of-Laramide time and the present day; Geomorphology, v. 75, no. 3-4, p. 450–477.

Osterkamp, W.R., Fenton, M.M., Gustavson, T.C., Hadley, R.F., Holliday, V.T., Morrison, R.B. and Toy, T.J. (1987): Great Plains; in Geomorphic systems of North America, W.L. Graf (ed.), Geological Society of America, Boulder, Colorado, p. 163–210.

Palmer, A.R. (1983); The Decade of North American Geology 1983 geologic time scale; Geology, v. 11, p. 503-504.

Pana, D.I. and van der Pluijm, B.A. (2014): Orogenic pulses in the Alberta Rocky Mountains: Radiometric dating of major faults and comparison with the regional tectono-stratigraphic record. Geological Society of America Bulletin, published online on 6 October 2014 as doi:10.1130/B31069.1.

Pettapiece, W.W. (1986): Physiographic subdivisions of Alberta; Land Resources Research Centre, Research Branch, Agriculture Canada, scale 1:1,500,000.

Price, R.A. (1994): Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin; in Geological Atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists and Alberta Research Council, p.13–24.

Prior, G.J., Hathway, B., Glombick, P.M., Pană, D.I., Banks, C.J., Hay, D.C., Schneider, C.L., Grobe, M., Elgr, R. and Weiss, J.A. (2013): Bedrock geology of Alberta; Alberta Energy Regulator, AER/AGS Map 600, scale 1:1 000 000, URL <http://ags.gov.ab.ca/publications/abstracts/MAP_600.html> [June 2014].

Proudfoot, D.N. (1985): A lithostratigraphic and genetic study of quaternary sediments in the vicinity of Medicine Hat, Alberta; Ph.D. thesis, University of Alberta, 248 p.

Russell, L.S. (1950): The Tertiary gravels of Saskatchewan; Transactions of the Royal Society of Canada, ser. 3, v. 44, sec. 4, p. 51-59.

Russell, L.S. (1952): Age of the Front-Range deformation in the North American Cordillera; Transactions of the Royal Society of Canada, ser. 3, v. 45, sec. 4, p. 47–69.

Russell, L.S. and Landes, R.W. (1940): Geology of the southern Alberta plains; Geological Survey of Canada, Memoir 221, 223 p.

Russell, L.S. and Wickenden, R.T.D. (1933): An upper Eocene vertebrate fauna from Saskatchewan; Transactions of the Royal Society of Canada, ser. 3, v. 27, sec 4, p. 53–66.

Rutherford, R.L. (1937): Saskatchewan Gravels and Sands in central Alberta; Transaction of the Royal Society of Canada, ser. 3, v. 31, sec. 4, p. 81–95.

Salvador, A. (1994): International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology and Procedure, 2nd Edition; Geological Society of America, Boulder, CO, p. 1-214.

Stalker, A.M. (1963): Quaternary stratigraphy in southern Alberta; Geological Survey of Canada, Paper 62-34, 52 p.

Stalker, A.M. (1968): Identification of Saskatchewan Gravels and Sands; Canadian Journal of Earth Sciences, v. 5, no. 1, p. 155–163.

Stalker, A.M. (1969): Quaternary stratigraphy in southern Alberta-Report II, sections near Medicine Hat; Geological Survey of Canada, Paper 69-26, 28 p.

Stalker, A.M. (1973): Surficial geology of the Drumheller area, Alberta; Geological Survey of Canada, Memoir 370, 122 p.

Stalker, A.M. (1976): Quaternary stratigraphy of the southwestern Canadian prairies; in Quaternary Stratigraphy of North America, W.C. Mahaney. (ed.), John Wiley & Sons, Hoboken, New Jersey, p. 381–407.

Stalker, A.M. (1977): The probable extent of classical Wisconsin ice in southern and central Alberta; Canadian Journal of Earth Sciences, v. 14, no. 11, p. 2614–2619.

Stalker, A.M. (1983): Quaternary stratigraphy in southern Alberta-Report III: the Cameron Ranch Section; Geological Survey of Canada, Paper 83-10, 20 p.

Stalker, A.M. and Harrison, J.E. (1977): Quaternary glaciation of the Waterton-Castle River region of Alberta; Canadian Society of Petroleum Geologists Bulletin, v. 25, no. 4, p. 882–906.

Stalker, A.M. and Wyder, J.E. (1983): Borehole and outcrop stratigraphy compared with illustrations from the Medicine Hat area of Alberta; Geological Survey of Canada, Bulletin 296, 28 p.

Storer, J.E. (1978): Tertiary sands and gravels in Saskatchewan and Alberta: correlation of mammalian faunas; in Western and Arctic Canadian biostratigraphy: proceedings of the P. S. Warren Biostratigraphy Symposium organized by the Geological Association of Canada and the Edmonton Geological Society, held at the University of Alberta, Edmonton, Alberta, May 19, 1976, C.R. Stelck and B.D.E. Chatterton (ed.), p. 595–602.

Storer, J.E. (1996): Eocene-Oligocene faunas of the Cypress Hills Formation, Saskatchewan; in The terrestrial Eocene-Oligocene transition in North America, D.R. Prothero and R.J. Emry (ed.), Cambridge University Press, p. 240–261.

Taylor, R.S., Mathews, W.H. and Kupsch, W.O. (1966): Tertiary; in Geological History of Western Canada, R.G. McCrossan and R.P. Glaister. (ed.), Alberta Society of Petroleum Geologists, Calgary, Alberta, p. 190–194.

Toth, J., Ozoray, G.F., Wallick, E.I., Bibby, R., Gabert, G.M., Stein, R. and Lytviak, A.T. (1977): Contributions to the hydrogeology of Alberta; Research Council of Alberta, Bulletin 35, 93 p., URL <http://ags.gov.ab.ca/publications/abstracts/BUL_035.html> [June 2014].

Vonhof, J.A. (1969): Tertiary gravels and sands in the Canadian Great Plains; Ph.D. thesis, University of Saskatchewan, 279 p.

Vreeken, W.J. (1989): Late Quaternary events in the Lethbridge area, Alberta; Canadian Journal of Earth Sciences, v. 26, no. 3, p. 551–560.

Vreeken, W.J. and Westgate, J.A. (1992): Miocene tephra beds in the Cypress Hills of Saskatchewan, Canada; Canadian Journal of Earth Sciences, v. 29, no. 1, p. 48–51.

Wagner, W.P. (1966): Correlation of Rocky Mountain and Laurentide glacial chronologies in southwestern Alberta, Canada; Ph.D. thesis, University of Michigan, 169 p.

Walker, R.G. (1979): Facies models; Geological Association of Canada, Toronto, Ontario, 211 p.

Warren, P.S. (1939): The Flaxville Plain in Alberta; Transaction of the Royal Canadian Institute, pt. 2, v. 22, no. 48, p. 341–349.

Westgate, J.A. (1965): The Pleistocene stratigraphy of the Foremost-Cypress Hills area, Alberta; Alberta Society of Petroleum Geologists 15th Annual Field Guidebook, Part I, Cypress Hills Plateau, p. 85–111.

Whitaker, S.H. and Christiansen, E.A. (1972): The Empress Group in southern Saskatchewan; Canadian Journal of Earth Sciences, v. 9, no. 4, p. 353–360.

Willis, B. (1902): Stratigraphy and structure, Lewis and Livingston ranges, Montana; Geological Society of America Bulletin, v. 13, p. 305–352.

Young, R.R., Burns, J.A., Smith, D.G., Arnold, L.D. and Rains, R.B. (1994): A single, late Wisconsin, Laurentide glaciation, Edmonton area and southwestern Alberta; Geology, v. 22, no. 8, p. 683–686.

Young, R.R., Burns, J.A., Rains, R.B. and Schowalter, D.B. (1999): Late Pleistocene glacial geomorphology and environment of the Hand Hills region and southern Alberta, related to middle Wisconsin fossil prairie dog sites; Canadian Journal of Earth Sciences, v. 36, no. 9, p. 1567–1581.