ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Dipartimento di Scienze della Terra
e Geologico-Ambientali

DOTTORATO IN SCIENZE DELLA TERRA
XXI° CICLO
Coordinatore: Prof. William Cavazza

Tesi di Dottorato

Stratigraphy and Palaeontology of the Late Cretaceous Wapiti Formation,

west-central Alberta, Canada

Stratigrafia e Paleontologia della Wapiti Formation (Cretaceo Superiore),

Alberta centro-occidentale, Canada

Presentata da:
Dr. Federico Fanti

Relatori:
Prof. Gian Battista Vai
Prof. Octavian Catuneanu

Bologna, 10 Marzo 2009

CONTENTS

Appendixes

Federico Fanti and Philip Currie, 2007:

A new *Pachyrhinosaurus* bonebed from the late Cretaceous Wapiti Formation

Federico Fanti, 2007:

Unfolding the geological history of the North: new comprehensive survey of the Wapiti Formation, Alberta, Canada

Federico Fanti and Octavian Catuneanu, 2008:

Sequence Stratigraphy of the Fluvial Wapiti Formation, Grande Prairie region, Alberta, Canada

Abstract

A complete stratigraphic assessment and revision of the middle Campanian to upper Maastrichtian Wapiti Formation in north-western Alberta and north-eastern British Columbia is the main aim of this research project. The study area encompasses an area of approximately 200X180 km in the Grande Prairie County (west-central Alberta) and easternmost British Columbia, Canada. Results presented here indicate that the 1300m thick succession currently reported in the literature as "*undifferentiated lithostratigraphic unit*", consists of five lithostratigraphic units and four unconformity-bounded depositional sequences; their study and description have been documented integrating several geological disciplines, including sequence stratigraphic methods, well-log signatures, facies analysis, and fossil associations. On the whole, particular attention has been given to 1) age and nature of both basal and upper contacts of the Wapiti Formation, 2) effective mappability of lithostratigraphic units and depositional sequences in western Alberta, and 3) the identification of previously undetermined maximum flooding surface of the Bearpaw seaway and Drumheller Marine Tongue, which are reference marine unit in central and southern Alberta. A second, but not less important, guideline for the project has been the rich paleontological record of the Wapiti deposits. Detailed paleoenvironmental and taxonomical information on old and new finds have been the base for correlation with well known associations of Alaska, southern Alberta, and Montana. Newly discovered rich fossil localities documented an extraordinarily diverse fauna during the latest Cretaceous, including dinosaurs, squamates, and fresh-water fishes and reptiles.

Lastly, in order to better characterize the Wapiti Formation, major marker beds were described: these include several bentonites (altered volcanic ash deposits) which have been documented over an area of almost 30.000 km^2, as well as four major coal zones, characterized by tabular coal seams with an overall thickness of 2 meters. Such marker beds represent a formidable tool for high-resolution chronology and regional correlations within the Late Cretaceous Alberta foreland basin.

Abstract

L'obiettivo di questo studio è una dettagliata revisione della Wapiti Formation (Campaniano-Maastrichtiano) che si estende nell'Alberta centro-occidentale e della British Columbia nord-orientale. L'area studio comprende una superficie di circa 200X180 km nella regione di Grande Prairie. I risultati ottenuti indicano che la successione dello spessore di circa 1300 metri correntemente indicata in letteratura come "*unità litostratigrafia indifferenziata*" consiste in cinque unità litostratigrafiche e quattro sequenze deposizionali a limiti inconformi. La loro descrizione e analisi si basa sull'integrazione di diversi approcci nell'ambito delle scienze geologiche, tra cui la stratigrafia sequenziale, analisi di log geofisici di sottosuolo, analisi di facies, analisi geochimiche e associazioni fossilifere. Nel complesso, particolare attenzione è stata rivolta a 1) età e natura dei contatti a base e a tetto della Wapiti Formation, 2) alla mappabilità delle unità litostratigrafiche e delle sequenze deposizionali a scala regionale e 3) all'identificazione delle maximum flooding surfaces della Bearpaw Formation e della Drumheller Marine Tongue, entrambe unità marine di riferimento nell'Alberta centrale e meridionale.

Al fine di verificare la presenza di livelli guida e soprattutto di verificare variazioni nell'area sorgente dei sedimenti della Wapiti Formation, diversi livelli bentonitici (documentati in un'area di circa 30.000 km^2) e importanti intervalli ricchi in strati di carbone sono stati descritti in dettaglio ed analizzati mediante studi di geochimica. Tali strati ed intervalli rappresentano un fondamentale strumento sia per correlazioni a scala locale e regionale che per l'inserimento delle diverse unità stratigrafiche in una scala temporale di riferimento.

Una seconda linea guida di questa ricerca è stata l'analisi del ricco contenuto paleontologico della Wapiti Formation. Una dettagliata analisi tassonomica e paleoambientale è stata fondamentale per le correlazioni biostratigrafiche con le note associazioni paleontologiche dell'Alaska, dell'Alberta meridionale e del Montana. La scoperta di nuove località fossilifere documenta una fauna straordinariamente diversificata durante il Cretaceo Superiore che include dinosauri, squamati, uccelli, e pesci e rettili di acqua dolce.

Introduction

1. Geological framework

The original geological studies of the uppermost Cretaceous-Tertiary strata in the Alberta foreland basin applied formational ranking to the facies associated with the three coarse-grained, diachronous sedimentary wedges, giving rise to names such as the Milk River, Belly River, and Edmonton groups. As further stratigraphic studies were completed, it became apparent that these strata were widely variable in thickness and lithofacies, resulting in the introduction of additional names to further refine the stratigraphic nomenclature. Where these additional formations have been defined, the original formation has commonly been elevated to group status, thus creating the Belly River Group, (Oldman and Foremost formations), the Edmonton Group, (Horseshoe Canyon, Whitemud, Battle and Scollard formations), and the Saunders Group, (Brazeau, Coalspur and Paskapoo formations). However, this process has not been undertaken universally across the basin, and has resulted in a confusing nomenclature. Further complicating the issue is the application of American stratigraphic terminology to define units in Canada, as exemplified by the introduction of the Judith River Formation (McLean, 1971) and Claggett Formation (Wasser, 1988). Within the context of this study, the stratigraphic nomenclature as shown on Figure 1 is applied.

Where the Belly River Group is undifferentiated, the name Belly River Formation is used. The Horseshoe Canyon Formation name is used and the term Edmonton Group disregarded to allow compatibility between equivalent formations in Alberta and Saskatchewan. Foothills nomenclature is that of Jerzykiewicz (1985). In northwest Alberta, strata equivalent to the Belly River, Horseshoe Canyon, and where present the Whitemud and Battle formations were previously jointly defined as the Wapiti Formation (Dawson et al., 1992).

The uppermost Cretaceous-Tertiary stratigraphic interval forms an integral part of the foreland basin of the Western Canada Sedimentary Basin. The formations that lie within this interval provide a unique geological record of the final development of the basin and the relation of that development to tectonics, eustasy and climate. The geological history of this interval can be interpreted in terms of a series of tectonic events to the west, with resultant erosion and widespread sediment supply into the basin, interspersed with periods of limited sedimentation and/or marine transgression. In the middle Campanian, (~78 Ma), during deposition of the Foremost Formation and basal Wapiti deposits, the source of sediment was principally normal to the deformation front (i.e. from the southwest).

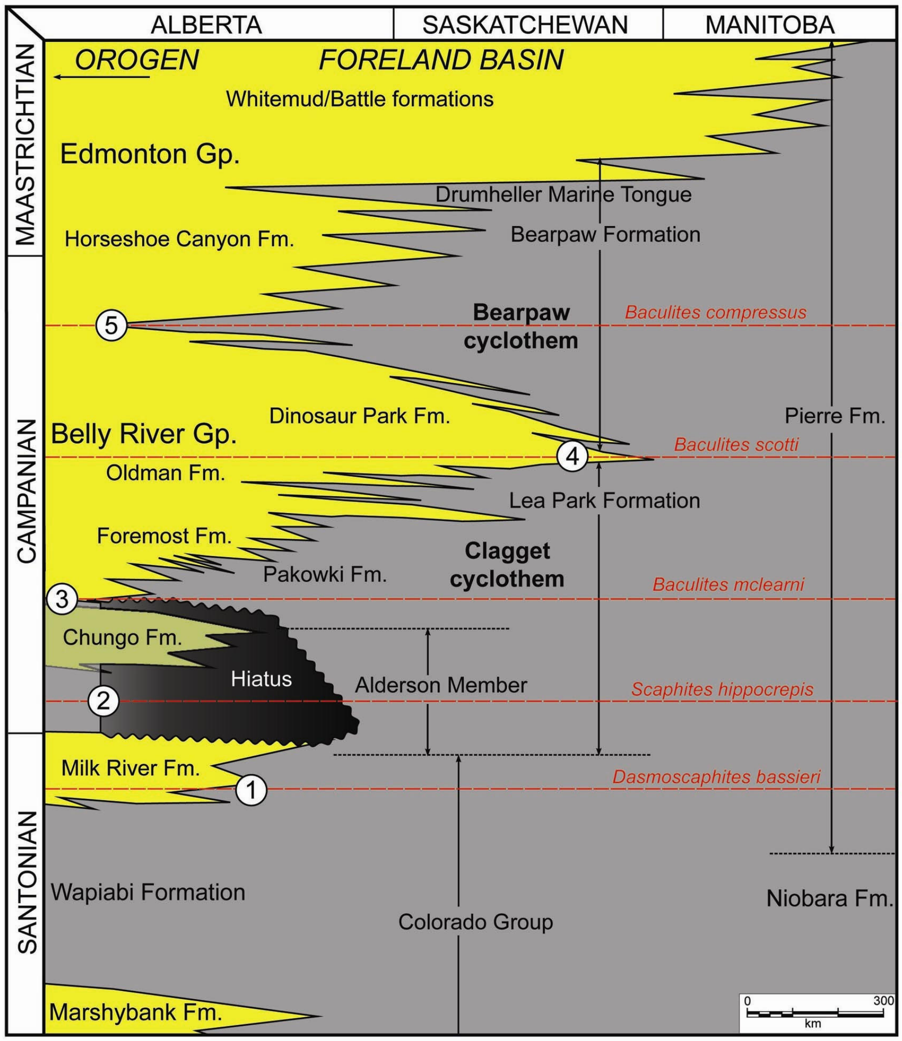


Figure 1: Schematic stratigraphic cross-section of late Cretaceous Western Canadian Sedimentary Basin. 1, *Desmoscaphites bassieri* 89.3 Ma, onset of Milk River regression. 2, *Scaphites hippocrepis* 81.7 Ma, major hiatus in southern Alberta. 3, *Baculites mclearni* 80 Ma, Claggett MFS. 4, *Baculites scotti* 76.4 Ma, Claggett MRS. 5, *Baculites compressus* 73.4 Ma, Bearpaw MFS. Modified after Mumpy and Catuneanu, 2007. Terrestrial deposits in yellow; marine successions in grey.

Later, during deposition of the Oldman Formation, the sediment source shifted to the west-northwest, probably as a result of reactivation of mountain building in the northern regions. Following the deposition of the Belly River wedge (lower Wapiti Formation), a widespread marine incursion from the southeast occurred, giving rise to the sediments of the Bearpaw Formation (~76 Ma). The Bearpaw Sea extended from southeast Saskatchewan to north of Edmonton. Farther to the north, beyond the limit of marine deposition, continental sedimentation continued unimpeded. Such deposits are represented by the late Campanian deposits of the Wapiti Formation (Figure 2)

The second major sedimentary wedge (Edmonton Group) prograded into a gradually retreating Bearpaw Sea during early Maastrichtian time (~73-70 Ma). The source of sediments was principally from the northwest and west. Depositional environments of the aggrading section varied from shallow marine and deltaic near the base to fluvial near the top. The upper strata of the Horseshoe Canyon Formation include a widespread coal zone (Carbon-Thompson), which is overlain by a distinctive, whitish, kaolinitic siltstone (Whitemud Formation) and dark grey mudstone (Battle Formation). This stratigraphic interval is represented by regionally extensive coals in the Wapiti Formation. It is probable that at this time (~66 Ma), the foreland basin was essentially filled, and that isostatic rebound of the basin accompanied by a major environmental shift may have been responsible for the regional disconformity at the top or within the Battle Formation (Figure 2).

Lastly, during the late Maastrichtian (~66-64 Ma), renewed tectonic activity and downwarping of the western half of the foreland basin led to the deposition of a third clastic wedge. The lower Scollard and its equivalents are essentially barren of coal and extend throughout most of the basin.

2. Wapiti Formation project

The Wapiti Formation, which outcrops extensively in northwestern Alberta and northeastern British Columbia, is a sedimentary succession that represents a time interval going from the middle Campanian to the early Maastrichtian. As such is temporally equivalent to the Belly River Group (Foremost, Oldman, and Dinosaur Park formations), the Bearpaw Formation, and the Edmonton Group (Horseshoe, Whitemud, and Battle formations) of southern and central Alberta (Eberth, 1990, 2002, 2005; Eberth and Hamblin, 1993; Dawson et al., 1994a, b; Jerzykiewicz and Norris, 1995; Eberth and Brinkman, 1997; Brinkman et al., 1998; Catuneanu et al., 2000; Bachu and Michael, 2003; Brinkman, 2003; Lerbekmo et al., 2003), all known for their abundance of fossil vertebrates and high diversity of dinosaur taxa. In the last decade, field activities in the Grande Prairie district resulted in the discoveries of several important fossil localities, among the richest ever found in Alberta and North America, which include hadrosaur and ceratopsian-dominated bonebeds, dinosaur skeletons, isolated material ascribed to tyrannosaurs and ankylosaurs, trackway localities, microvertebrate sites, insects in amber, and megaplant fossils. Despite these promising discoveries, the stratigraphy of the Wapiti Formation and its unique dinosaur faunas remained for decades virtually unknown. In fact, except for a few paleontological reports (Tanke, 2004) and articles on the coal potential of the region (Allan and Carr, 1946; Byrne, 1955; Stott, 1961; Dawson et al., 1994b), the geological and paleontological importance of the area has been unstudied. Factors such as remoteness of outcrops, vast extent of the study area, vegetation cover, and high operational costs have each played a role in restricting the paleontological study of the Wapiti Formation relative to the better known formations of southern Alberta.

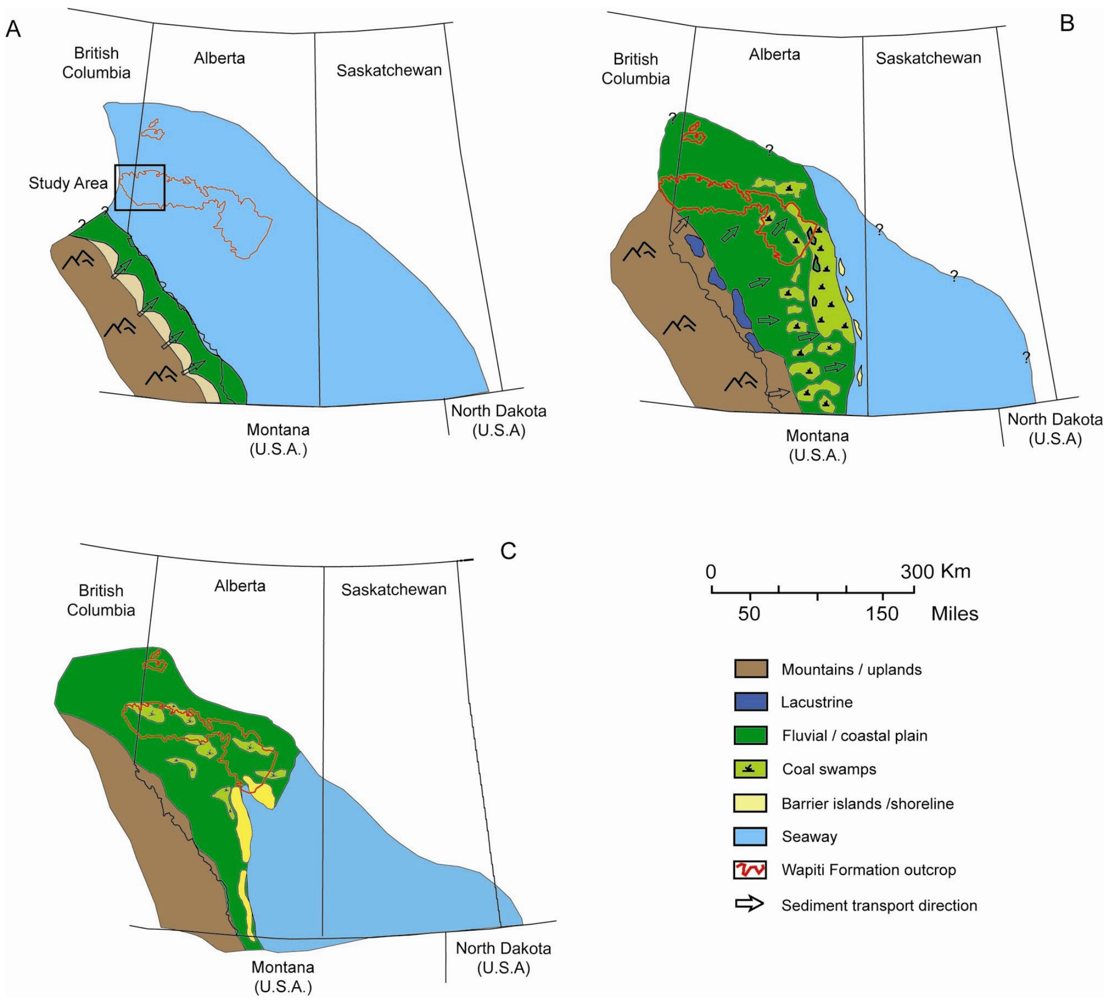


Figure 2: Schematic paleogeography during the deposition of the Wapiti and coeval successions in western Canada. A, 83 Ma, Lea Park Formation; B, 78 Ma, maximum Foremost Formation progradation; C, 73.4 Ma, maximum transgression of the Bearpaw seaway.

In the Grande Prairie area and farther west into British Columbia, the Cretaceous foreland basin pinches out along the Alberta Syncline, and because of the local geo-tectonic setting is entirely exposed along major and minor drainage systems. In addition, intense oil and gas exploration activity in this area provides excellent subsurface control. Major outcrops are situated on overall bidirectional pattern that reflects north-south oriented tributaries flowing into east-west trending rivers. In this study, helicopter and jet boat explorations were combined with surface mapping and outcrop description in order to map and collect data from as many locations as possible. Field activities were carried out over an area of approximately 19,500 km^2, from the Smoky River in the East (long. 118°) to Tumble Ridge, British Columbia in the west (long. 121°), and from the Grande Cache area in the south (lat. 54° 04') to Bad Earth Creek in the north (lat. 55° 40').

3. Objectives

The initial development of the research project has been following two main guidelines: the first integrate several geological approaches (geophysics, geochemistry, facies analyses, petrography, etc.) in order to provide an high resolution stratigraphic revision of the entire sedimentary succession and to refer discrete stratigraphic intervals, disconformities, marker beds, and major fossiliferous sites to a robust chronostratigraphic framework (Figure 3). The second one has the specific target to obtain detailed paleoenvironmental and taxonomical information to correlate vertebrate taxa from northern Alberta to those in Alaska, southern Alberta, and northern US. In fact it must be considered that the Wapiti succession lies in a relatively poorly known section of the Alberta foreland basin: lacking any marine depositional event, it plays a unique role in our understanding of basin fill timing and processes, as well as vertebrate dispersion and paleobiogeography along the western margin of the Western Interior Seaway (Figure 2).

4. Results

Five scientific papers form the bulk of this study: in addition, other related publications are included in the appendixes. In particular:

Paper 1: *Stratigraphy of the Upper Cretaceous Wapiti Formation, west-central Alberta, Canada.*
Accepted manuscript, Canadian Journal of Earth Sciences.

In this paper is discussed the subdivision of the Wapiti Formation into regionally mappable lithostratigraphic units and the correlation of such units with the better known successions of central and southern Alberta

Paper 2: *Bentonite chemical features as proxy of Late Cretaceous provenance changes: a case study from the Western Interior Basin of Canada.*
Accepted manuscript, Sedimentary Geology.

In this study is presented a comparative analysis of geochemical compositions between Grande Prairie bentonites and 30 known volcanic beds from central and southern Alberta, Manitoba and Montana.

Paper 3: *Fluvial sequence stratigraphy: the Wapiti Formation, west-central Alberta, Canada.* Accepted manuscript, Journal of Sedimentary Research.

In this paper are defined depositional sequences in the Wapiti Formation providing a case study where 1) both *downstream* and *upstream* controls on fluvial processes can be discussed, and 2) regionally extensive coal seams represent MFSs within proximal, exclusively alluvial deposits.

Paper 4: *A high latitude vertebrate fossil assemblage from the Late Cretaceous of west-central Alberta, Canada: evidence for dinosaur nesting and vertebrate latitudinal gradient.*
In press., Palaeoegeography, Palaeoecology, Palaeoclimatology.

This paper consists of a detailed paleoecological and taxonomical analyses of a new microsite and a discussion on its stratigraphic and palaeobiogeographical implications. The site represent the northernmost dinosaur nesting ground in North America known to date. Taxa recovered at the site provide insights into Late Cretaceous vertebrate latitudinal gradient along the Western Interior Basin.

Paper 5: *Upper Campanian Borioteiioidean lizards from Kleskun Hill, West-Central Alberta (WapitiFormation), Canada.*
Accepted manuscript, Journal of Vertebrate Paleontology

This study reports on the northernmost occurrence of articulated specimens of teiid lizards (the sole record for the Late Cretaceous) in North America. Cranial elements are ascribed to a juvenile individual of *Socognathus unicuspis* and to *Kleskunsaurus grandeprairiensis* (n. gen., nov sp.).

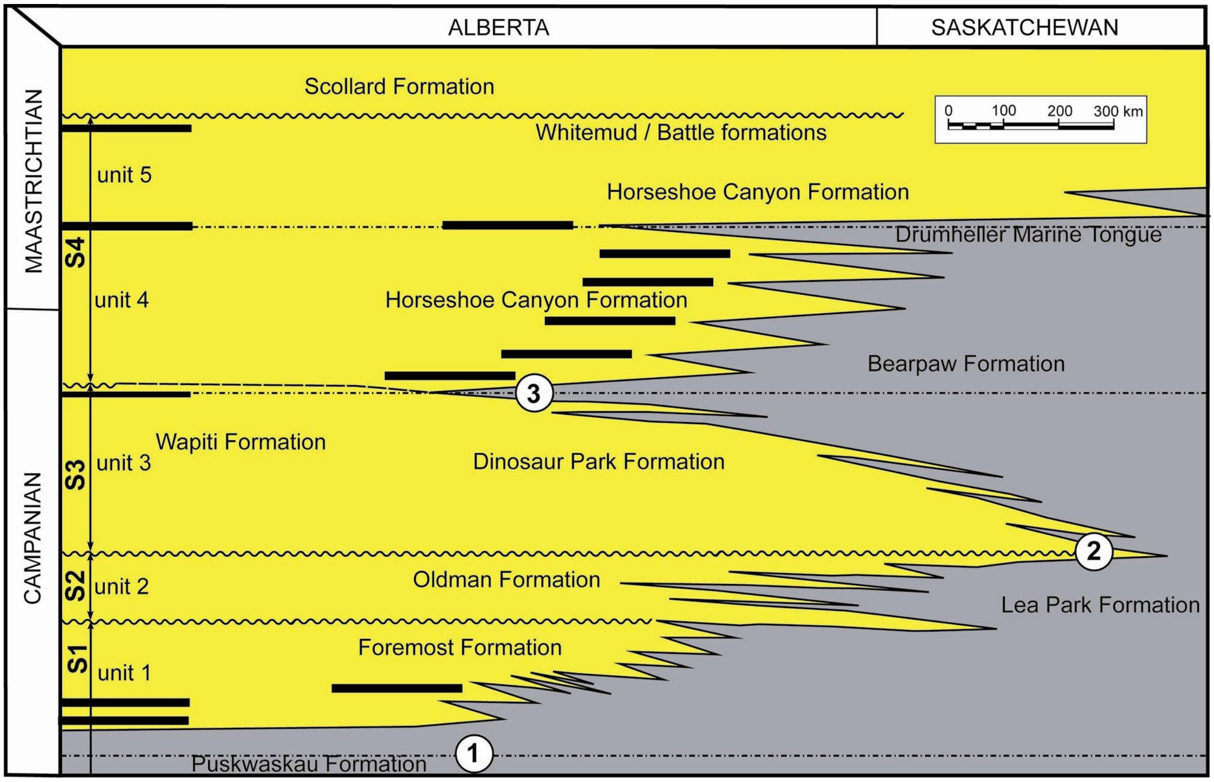


Figure 3: Schematic stratigraphic cross-section of Late Cretaceous Western Canadian Sedimentary Basin showing newly proposed lithostratigraphic units (unit 1-5) and unconformity bounded depositional sequences (S1-4). 1, Puskwaskau/Claggett MFS. 2, Claggett MRS. 3, Bearpaw Formation MFS. Black boxes indicate major coals. Terrestrial deposits in yellow; marine succesisons in grey.

Lastly, additional publications resulted by projects carried out along with the Ph.D. thesis are included as Appendixes. Relevant data on palynology, radioisotopic ages, and fossil sites are currently under study for further publications.

References

Allan, J., Carr, J., 1946. Geology and coal occurrences of Wapiti-Cutbank area, Alberta. Research Council of Alberta Report 48, 50 pp.

Bachu, S., Michael, K., 2003. Possible controls of hydrogeological and stress regimes on the producibility of coalbed methane in upper Cretaceous – Tertiary strata of the Alberta Basin, Canada. AAPG Bulletin 87, 1729-1754.

Byrne, P., 1955. Bentonite in Alberta. Research Council of Alberta Report 71, 17 pp.

Brinkman, D., Ryan, M., Eberth, D., 1998. The paleogeographic and stratigraphic distribution of Ceratopsid (Ornithischia) in the Upper Judith River Group of Western Canada. Palaios 13, 160-169.

Brinkman, D., 2003. A review of nonmarine turtles from the late Cretaceous of Alberta. Canadian Journal of Earth Sciences 40, 557-571.

Catuneanu, O., Sweet, A., Miall, A., 2000. Reciprocal stratigraphy of the Campanian–Paleocene Western Interior of North America. Sedimentary Geology 134, 235-255.

Dawson, F., Kalkreuth, W., and Sweet, A., 1992: Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta. Geological Survey of Canada, Open File report 2499, 98 p.

Dawson, F., Evans, C., Marsh, R., Richardson, R. 1994a. Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin. In: Mossop, G., and Shetson, I. (Eds.), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, chapter 24, 18 pp.

Dawson, F., Kalkreuth, W., Sweet, A., 1994b. Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta. Geological Survey of Canada Bulletin 466, 60 pp.

Eberth, D., 1990. Stratigraphy and sedimentology of vertebrate microfossil sites in the uppermost Judith River Formation (Campanian), Dinosaur Provincial Park, Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 78, 1-36.

Eberth, D., 2002. Review and comparison of Belly River Group and Edmonton Group stratigraphy and stratigraphic architecture in the southern Alberta plains. Canadian Society of Petroleum Geologists, Diamond Jubilee Convention, Program and Abstract 117. Abstracts of Technical Talks, Poster and Core Displays including Extended abstracts. PDF file 227S0125 CD.

Eberth, D., 2005. The geology. In: Currie P., and Koppelhus, E. (Eds.), Dinosaur Provincial Park, a spectacular ecosystem revealed. Indiana university Press, Bloomington, chapter 3, 54-82.

Eberth, D., Hamblin, A., 1993. Tectonic, stratigraphy, and sedimentologic significance of a regional discontinuity in the upper Judith River Group (Belly River wedge) of southern Alberta, Saskatchewan, and northern Montana. Canadian Journal of Earth Sciences 30, 174-200.

Eberth, D., Brinkman, D., 1997. Paleoecology of an estuarine, incised valley fill in the Dinosaur Park Formation (Judith River Group, Upper Cretaceous) of southern Alberta, Canada. Palaios 12, 43-58.

Jerzykiewicz, T., 1985: Stratigraphy of the Saunders Group in the central Alberta Foothills - a progress report. In: Current Research, Part B, Geological Survey of Canada, Paper 85-1B, p. 247-258.

Jerzykiewicz, T., Norris, D., 1999. Stratigraphy, structure and syntectonic sedimentation of the Campanian "Belly River" clastic wedge in the southern Canadian Cordillera. Cretaceous Research 15, 367-399.

Lerbeckmo, J., Braman, D., Catuneanu, O., Humprey, N., 2003. Magnetostratigraphic and palynostratigraphic correlation of late Campanian strata of the Bearpaw and Horseshoe Canyon formations of the RCA Castor corehole to the Red Deer Valley, Alberta. Bulletin of Canadian Petroleum Geology 51, 70-77.

McLean, J., 1971: Stratigraphy of the Upper Cretaceous Judith River Formation in the Canadian Great Plains. Saskatchewan Research Council, Geological Division, Report 11, 96 p.

Mumpy, A., and Catuneanu, O., 2007: Controls on Accommodation in Retroarc Foreland Systems: Case Study of The Lea Park Formation and Equivalents, Western Canada Sedimentary Basin. American Association of Petroleum Geologists Annual Convention and Exhibition, Abstracts Volume p. 99.

Stott, D., 1961. Dawson Creek map area, British Columbia. Geological Survey of Canada, Paper 61-10.

Tanke, D., 2004. Mosquitoes and mud – The 2003 Royal Tyrrell Museum of Paleontology expedition to the Grande Prairie region (north-western Alberta, Canada). Alberta Paleontological Society Bulletin 19, 3-31.

Wasser, G., 1988: A geological evaluation of the Judith River Formation (Belly River Formation) in the Pembina region. In: Sequences, Stratigraphy, Sedimentology: Surface and Subsurface. D. James and D. Leckie (eds). Canadian Society of Petroleum Geologists, Memoir 15, p. 563-570.

Paper 1

Stratigraphy of the Upper Cretaceous Wapiti Formation,
West-Central Alberta, Canada

Federico Fanti and Octavian Catuneanu

Federico Fanti
Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Università di Bologna,
Via Zamboni 67, 40126 Bologna, Italy
Corresponding author: Tel: +39 051 2094565; Fax: +39 051 2094522;
Email: federico.fanti@unibo.it

Octavian Catuneanu
Department of Earth and Atmospheric Sciences, University of Alberta
1-26 Earth Sciences Building, Edmonton, Alberta, Canada
Email: octavian@ualberta.ca

Abstract

The lithostratigraphic interval between the marine Puskwaskau Formation (Smoky Group, Santonian-Campanian) and the fluvial Scollard Formation (early Maastrichtian) in west-central Alberta and easternmost British Columbia (Canada) is represented by the non-marine deposits of the Wapiti Formation. Its subdivision into regionally mappable stratigraphic units and the correlation of such units with the better known successions of central and southern Alberta are the main goals of this study. We present a detailed stratigraphic revision of the Wapiti Formation in the Grande Prairie Region, where the entire succession crops out extensively and intensive oil and gas exploration activity provides excellent subsurface control. This study indicates that the Wapiti Formation consists in five stratigraphic units: their description has been based in particular on facies analysis and well-log signatures. In ascending order, units 1 to 5 record major differences in depositional architecture related to variation in accommodation and climatic conditions. Upper and lower contacts of these units are represented by regionally mappable subaerial unconformities or conformable facies contacts. Three major coal zones are identified within the Wapiti Formation, the Basal, Red Willow, and Cutbank: coals referred to these intervals have been documented in both outcrop and subsurface in the entire study area, thus representing a reliable tool for regional correlations. Furthermore, results presented here indicate that the maximum flooding surfaces of the Bearpaw seaway and the Drumheller Marine Tongue, both marine reference units in central and southern Alberta, lie respectively within coals of unit 3 and the Red Willow coal zone.

Introduction

The Wapiti clastic wedge constitutes the product of a complex interaction between tectonic activity in the Canadian Cordillera, climatic fluctuations, and sediment supply. This interaction resulted in accommodation changes, depocenter migration, and paleoenvironmental shifts in the northernmost section of the Alberta foreland basin during Campanian-Maastrichtian time. A systematic revision of the entire Wapiti Formation based on new outcrop and subsurface data from the Grande Prairie region in west-central Alberta indicates that the stratigraphic interval between the Santonian/Campanian, marine Puskwaskau Formation (Smoky Group), and the Maastrichtian Entrance Member (Scollard Formation), consists of five distinct stratigraphic units (Fig. 1). The separation and mapping of these units on a regional scale raises important questions and produces new insights with respect to the relationships between 1) tectonism and sediment supply, 2) depositional trends and stratal stacking patterns, and 3) the evolution of paleo-depositional environments represented within the Wapiti Formation. The three-dimensional stratigraphic data presented here allowed for a detailed analysis of sequence geometries and lithofacies distribution through a succession that consists of approximately 1300 meters of exclusively non-marine deposits at its western edge. In addition, palynological, biostratigraphic, and radioisotopic data support a more accurate correlation between the Wapiti deposits and correlative units of the Alberta basin both spatially and temporally. Particular attention was given to the age and nature of the lower and upper Wapiti boundaries and to the stratigraphic contacts between identified subdivisions (i.e., units 1 to 5), as well as to the recognition of previously unstudied inland deposits equivalent to the sediments of the Bearpaw Formation and Drumheller Marine Tongue, both important stratigraphic reference units in central and southern Alberta. Results presented in this study give insight into the evolution of the Wapiti depositional system and provide a strong stratigraphic context for the fossiliferous localities and paleoenvironmental indicators found within these deposits. Finally, in this paper we relate the stratigraphic units of the Wapiti Formation with the latest Cretaceous evolution of the Alberta foreland basin and propose a new stratigraphic subdivision for this interval in north-western Alberta.

Previous Work

Historically, the term Wapiti was first used by Dawson (1881) to identify approximately 90 meters of non-marine strata overlying dark marine shales along the Smoky River (Smoky Group) in the Grande Prairie region. McLearn (1919) extended the overall thickness to 275 meters by including outcrops along the Smoky River south of the town of Bezanson (25 km east of Grande

Prairie), and considered the base of the fluvial succession to be correlative with the base of the Foremost Formation of southern Alberta. Additional early studies on these deposits carried out by Evans and Caley (1929), Rutherford (1930), Hackbarth (1946), Gleddie (1949), and Ryan (1989) were all regional in scope, and focused primarily on near-surface coal and water resources. Allan and Rutherford (1934) indicated the Wapiti Formation to be correlative with the entire Belly River to Edmonton successions described by Selwyn (1874) in central and southern Alberta "*on a lithological basis*". Later works by authors such as Evans and Caley (1929), Allan and Carr (1946), Gleddie (1949), Byrne (1955) and particularly Stott (1961) gradually expanded the geological framework to include outcrops along the Cutbank and Kakwa Rivers and farther west in British Columbia (Fig. 1). Irish (1970) extended the Edmonton Group to the area between the Athabasca and Smoky Rivers, indicating that the Wapiti Formation was restricted to the Grande Prarire area. Green (1972) mapped the entire succession overlying the Lea Park Formation north of the Edmonton region as Wapiti Formation, including Belly River and Edmonton equivalent strata. The most recent revisions to the Wapiti were carried out by Chu (1978) and Dawson et al. (1994a, b) in the Edmonton and Grande Prairie areas respectively. To date, the most significant contributions to our understanding of the Wapiti beds are from local studies on coal, pollen, and magnetostratigrapy (Allan and Carr 1946; Kramers and Mellon 1972; Dawson and Kalkreuth 1989; Bustin and Smith 1993; Dawson et al. 1994a, b). However, little attention has been given to a formal subdivision of the Wapiti Formation. The current literature describes this succession as an undifferentiated lithostratigraphic unit that includes interbedded alluvial sediments, coal seams, and subordinate lacustrine deposits (Dawson et al. 1994a). The Wapiti clastic wedge reaches an overall thickness of 1300 metres along the eastern edge of the foothills and thins gradually to the north, where underlying stratigraphic units crop out in the plains. The Wapiti Formation is present along both sides of the Alberta Syncline which gives the unit an overall broad, synclinal geometry. Near the Alberta-British Columbia border, the sedimentary basin pinches out to the northwest, giving the syncline a south-eastward plunge.

Stratigraphy and stratigraphic nomenclature

In the foothills region of west-central Alberta the stratigraphic interval between the lower Santonian Bad Heart Formation and the Campanian Wapiti beds is represented by the Wapiabi and Puskwaskau formations. These marine units are correlative to the Lea Park and Milk River Formations of southern Alberta and southwestern Saskatchewan (Hu 1977; Rosental and Walker 1987; Braman and Hills 1990; Sweet and Braman 1990; Chen and Bergman 1999; Nielsen et al. 2003; Stancliffe and McIntyre 2003), as well as to the Wapiabi Formation of the Alberta (Colorado)

Group (Plint et al. 1990; Hu 1997; Chen and Bergman 1999; Braunberger and Hall 2001; Cobban et al. 2005). The Wapiti Formation is temporally equivalent to the Belly River Group (Foremost, Oldman, and Dinosaur Park formations), the Bearpaw Formation, and the Edmonton Group (Horseshoe, Whitemud, and Battle formations) of southern and central Alberta (Rahmani and Lerbekmo 1975; Stelck 1975; Eberth 1990, 2002, 2005; Eberth and Hamblin 1992; Dawson et al. 1994a; Jerzykiewicz and Norris 1994; Eberth and Brinkman 1997; Brinkman et al. 1998; Catuneanu et al. 2000; Bachu and Michael 2003; Brinkman 2003; Lerbekmo et al. 2003; MacEachern and Hobbs 2004). This succession correlates to the southwest with the Brazeau and Coalspur formations (Rahmani and Lerbekmo 1975; Dawson at al. 1989, 1994a; Osborn et al. 2006). In the study area, the marine Bearpaw Formation is absent and strata equivalent to both the Whitemud and Battle formations are difficult to identify individually both in outcrop and subsurface.

Allan and Carr (1946) proposed the first stratigraphic subdivision of the Wapiti beds. They established five informal members based on lithological variations observed along the Smoky, Cutbank, and Kakwa rivers (Fig. 1). However, these members were not placed within a chronostratigraphic framework nor were their lateral variations documented. Dawson and Kalkreut (1989) and later Dawson et al. (1994b) presented detailed description of major coal deposits within the Wapiti Formation and documented the presence of a marker coal bed in lowermost Wapiti beds cropping out along the Smoky River, as well as two extensive coal zones referred to here as the Red Willow and Cutbank coal zones (Fig. 1). Based on palynological data, the Red Willow coal zone is believed to be latest Campanian to earliest Maastrichtian in age (*Aquilapollenites clarireticulatus*, *A. tialatus*, *Mancicorpus calvus*, *Trudopollis meekeri*, and *Kurtziptes andersonii* association). The Cutbank coal zone is considered coeval to the Carbon and Thompson coal zones in the Alberta plains (Gibson 1977; McCabe et al. 1989) along with age-equivalent deposits of the upper Brazeau Formation (Maastrichtian, *Scollardia trapaformis* zone; see also Srivastava 1970; Jerzykiewicz and Sweet 1988; Sweet et al. 1989).

In this study we recognize five stratigraphic units based on new data acquired through multiple approaches including facies analysis, fossil associations, petrology, well log analysis, radioisotopic dating, and sequence stratigraphy (Fig. 1).

Paleontology

In the last decade, field activities in the Grande Prairie area have resulted in the discovery of several important fossil localities, some among the richest ever found in Alberta and North America. The temporal and geographic distribution of the Wapiti Formation fossiliferous beds has enormous potential for correlation and comparison with other faunal assemblages discovered throughout the Western Interior and farther north in Alaska. These include dinosaur bonebeds and skeletons, trackway localities, insects in amber, and megaplant fossils (Tanke 2004, 2006; Fanti and Currie 2007; Currie et al. 2008; Fanti and Miyashita *in press*.). Among the most important discoveries is the horned dinosaur genus Pachyrhinosaurus (*Pachyrhinosaurus lakustai* from Pipestone Creek and *Pachyrhinosaurus* sp. from the Wapiti River: Fanti and Currie 2007; Currie et al. 2008) which have been previously reported from the Prince Creek Formation of Alaska (Fiorillo and Gangloff 2003) and the Horseshoe Canyon and St. Mary River formations of central Alberta (Sternberg 1950; Langston 1967, 1975; Sampson and Loewen 2007).

Study Area

The Wapiti Formation crops out along a 500 X 150 km section of the Western Interior Basin, stretching from the Edmonton region in Alberta to easternmost British Columbia, east of the town of Tumbler Ridge (Fig. 2). In the Grande Prairie area and farther west into British Columbia, the Cretaceous foreland basin pinches out along the Alberta Syncline. Due to local highs and uplift originated by the Peace River Arch (Cant 1988; O'Connel et al. 1990; Kauffman and Caldwell 1993; Chen and Bergman 1999) the Wapiti Formation is entirely exposed along major and minor drainage systems. Intense oil and gas exploration in this area also provides excellent subsurface control. Nevertheless, factors such as the remoteness of exposures, fieldwork costs, and dense vegetation cover limited previous research on the Wapiti Formation. The study area is incised by major rivers such as the Smoky, Wapiti, Kakwa, Cutbank, and Simonette, and by several minor drainage systems which include Belcourt, Pinto, Pipestone, Spring, Mountain, and Bear Creeks. The succession reaches its maximum thickness along the Cutbank River where uppermost Wapiti and Scollard (Entrance Member) deposits are exposed. The basin pinches out to the northwest in British Columbia, where the basal Puskwaskau-Wapiti transition crops out extensively along Belcourt Creek and Wapiti River (approximately 10 km west of the Alberta-British Columbia border). Major outcrops are situated on an overall bidirectional pattern that reflects north-south oriented tributaries flowing into east-west trending rivers. Field activities were carried out from 2004 to 2008 over an area of approximately 19,500 km^2, from the Smoky River in the East (long. 118°00') to Tumbler Ridge, British Columbia, in the west (long. 121°00'), and from the Grande Cache area in the south (lat. 54°04') to the Bad Earth Creek in the north (lat. 55°40'). To better define the 3D geometry of the basin and these sedimentary units, subsurface data were used from the region east of the Smoky River, south of its confluence with the Wapiti River (Fig. 2).

Methods

The development of a robust stratigraphic scheme for the study area was initiated to provide a framework within which detailed and more localized geological observations could be placed. This new framework was used to describe the overall geometries of the Wapiti clastic wedge in the study area and to provide a detailed description of major stratigraphic markers and surfaces within the succession. Because no continuous cores were available in the study area, geophysical well logs were relied upon to correlate major stratigraphic unconformities and marker beds (i.e., extensive coal seams, bentonites, distinctive lithological units and contacts). Well logs were calibrated with outcrop data to develop reliable composite sections. All datasets were ultimately combined and used to create detailed three-dimensional models of the clastic wedge. Results were finally compared and integrated with data from Dawson et al. (1994b) and McMechan and Dawson (1995).
Each stratigraphic unit was described in terms of overall architecture, sedimentology (including pedology), and major paleontological characteristics; paleocurrent directions were measured from various sedimentary features (predominantly tabular and trough cross-stratified structures) and plotted as rose diagrams for each unit. Thin section analyses were performed on fourteen sandstone beds considered representative of key stratigraphic intervals.

Subsurface data

Construction of a robust stratigraphic framework using geophysical data is commonly difficult in fluvial strata because they contain channelized sand bodies of limited lateral extent. Detailed well-to-well correlations are particularly problematic when the adjacent wells are far apart relative to the width of sand bodies (e.g., Bridge and Tye, 2000). Gamma ray logs from 266 wells (Fig. 3) were used to assemble SW-NE dip-oriented and NW-SE strike-oriented sections which span the interval from the uppermost Puskwaskau Formation through approximately 500 meters of the Wapiti Formation (Figs. 4 and 5). Measurements of outcrops along with well-to-well correlations were used to estimate the geometry of isolated channel belts. Well 07-27-068-11W6/0 (lat. 54°91'; long. 119°58', elev. 757 m) is the reference log used in this study to exemplify typical unit thicknesses and the occurrence of marker beds; this well is located southwest of Grande Prairie approximately 3.5 km from the Wapiti River valley.

Outcrop and subsurface data from 550 exploration boreholes were used to construct the first structure contour map of the Puskwaskau-Wapiti contact as well as a detailed Wapiti isopach map (Fig. 6). Models show the sub-vertical folded strata along the present day deformation margin responsible for the rapid dipping to the west and southwest, as well as the syncline axis and the location of the depocenter. Examination of a large number of well logs and exposures suggests that no vertical displacement related to local fault systems occurs within the Wapiti beds. Field observations also indicate that Wapiti strata dip gently to the west (<7°) in areas east of the confluences of Calahoo and Little Muddy Creeks with the Wapiti River (Township 68, Ranges 11-12). To the west of this area, the strata dip eastward. Similarly, dip and strike measurements taken along Pinto Creek indicate that strata located south of Township 67 dip northward, whereas strata along the Wapiti River and north of the syncline axis dip to the southwest. This is consistent with data reported by Dawson et al. (1994b) who indicated that the axis of the syncline extended from Township 58, Range 1 to Township 64, Range 6 (page 15) based on field observations along the Cutbank and Kakwa rivers near their confluences with the Smoky River. Northward projection of the axis suggests that the syncline may extend as far as Township 71.

Stratigraphy

Puskwaskau-Wapiti transition

Although many previous studies have focused on detailed sedimentological and stratigraphic analyses of the Puskwaskau Formation (e.g., Stott 1961, 1967; McNeil and Caldwell 1981; Plint et al. 1990; Leckie et al. 1994; Hu 1997; Chen and Bergman 1999; Collom 2001, and references therein), none provided a full description of the nature of the transition from the marine Puskwaskau shales to the fluvial deposits of the Wapiti Formation. This transitional takes place over an interval up to 30 m thick, and is represented by a conformable shift from marine shale to coastal and fluvial deposits. Such interval is indicated in the literature as the Nomad Member of the Puskwaskau Formation (Stott 1963, 1967, Rosental and Walker 1987; Plint et al. 1990; Leckie et al. 1994). In the study area it consists largely of organic rich shales with interbedded bioclastic tempestites in the lower section and regressive, intensively bioturbated sandstones at the top (Fig. 7). In particular, facies identified within this transitional interval include, in ascending order: 1. offshore shale, 2. interbedded offshore shale and sandstone with frequent bioclastic tempestites and rippled/hummocky cross-stratified beds, 3. shoreface sandstone, 4. foreshore deposits (horizontally laminated, fine-to-medium grained sandstones), and 5. non-marine fluvial sandstone and silt (includes trough cross-bedded and rippled channel or crevasse splay sandstones).

Exposures of this stratigraphic interval are located along both sides of the Smoky River approximately 55 km northeast of Grande Prairie, and along most of Belcourt Creek in British Columbia, upstream from its confluence with the Wapiti River (Fig. 6). This conformable succession shares several similarities with the correlative Lea Park Formation – Belly River Group transitional deposits described by Power and Walker (1996) and Hamblin and Abrahamson (1996). For the purpose of correlation, the marine shales of the Nomad Member where sampled in order to document and compare the faunas (i.e., foraminifera, ammonites, bivalves, and vertebrates; see also Collom, 2001 for the systematic palaeontology of the Puskwaskau Formation). Despite the presence of fluvial/current transported organic remains (i.e., stumps, leaves, and possibly carcasses), along with fairly common burrowing structures within silty and sandy deposits, no microfossils have been preserved within the Puskwaskau marine shale.

Wapiti Formation - unit 1

This transitional unit reflects the early progradation of the Wapiti clastic wedge during the lower-middle Campanian (Fig. 8A).Large and continuous sections of this interval are exposed in British Columbia along the Wapiti River, along both sides of the Smoky River north of Grande Prairie, and in several isolated outcrops to the north in the Saddle Hills – White Mountain range area (located between Grande Prairie and Spirit River). Overall, unit 1reaches 100 m in thickness and consists of medium- to coarse-grained tabular channel sandstones interbedded with organic-rich mudstone, coal seams, and minor lacustrine deposits. The lower boundary of unit 1, and therefore of the entire Wapiti Formation, is defined by the first laterally persistent coal seam which occurs at the top of the transitional and deltaic deposits which belong to the Puskwaskau Formation (Figs. 7 and 8). This coal layer has an average thickness of 1.5 meters, is traceable on gamma ray logs throughout the entire study area, and was previously observed along the Smoky River (the "Basal Marker Coal" of Dawson et al. 1994b). The basal coal layer is likely the result of high water table and associated swampy conditions in a low gradient, coastal plain setting.

The lower 50 meters of unit 1 are characterized by meter-thick, laterally continuous coal seams that may be grouped into a single coal zone comparable in age and thickness to the McKay Coal Zone of southern Alberta (Gleddie 1949; Macdonald et al. 1987; Smith et al. 1994; Hamblin and Abrahamson 1996; Beaton et al. 2006). This interval corresponds to the first major peat accumulation within the continental sediments of the Wapiti Formation. Well log and outcrop analyses indicate that up to eight widespread, meter-thick coal seams lie within this interval suggesting deposition in water saturated environments, such as coastal organic-rich ponds or marshes (see also Figs. 4 and 5). Lacustrine deposits are also preserved throughout the unit: such deposits are finely laminated, locally varved, and are rich in organic components (including well preserved leaves and megaplant remains, seeds, and amber). Overbank and crevasse splay deposits are commonly interbedded with tabular coal seams and coal lenses, peat swamp deposits, and lenticular ironstone beds. Channel and overbank deposits are characterized by well clustered and sorted pebbles interbedded with large plant remains, indicating a high-energy hydraulic regime. Channel fill successions and crevasse splays are usually in the range of 1-2 meters in thickness, with isolated occurrences of up to 5 meters thick. Bentonitic beds are sporadic and commonly preserved as cm-thick lenses within the overbank setting.

Paleocurrent measurements (n=65) indicate a predominantly southwest – northeast flow direction in the western edge of the study area (N10°E, i.e., Belcourt Creek and Wapiti River) and a more west – east trend in stratigraphically younger deposits exposed to the north (N75°E, i.e., Saddle Hills, White Mountain, Smoky River, Woking). Such data are comparable to those reported by Hamblin and Abrahamson (1996, figure 12) for the Basal Belly River sand units. The stacking pattern of alluvial deposits varies vertically from strongly progradational in the lower part of the section to aggradational near the top of the unit. The transition to the overlying unit 2 is easily recognized both on well logs and in outcrop by the first appearance of meter to decameter-thick sandy channel fill successions (alluvial plain), and a major shift in depositional architecture from high to low accommodation (i.e., from a floodplain-dominated succession to amalgamated channel fills; see Catuneanu et al. 2009, for definitions of low versus high accommodation settings).

Wapiti Formation - unit 2

At the base of unit 2, the widespread, tabular coal seams of unit 1 are replaced by thinner and discontinuous coal beds and lenses (Fig. 8B). This change accompanied a major shift in depositional environment, which produced a widespread, regionally mappable, stratigraphic contact between the fine, organic rich deposits of unit 1, and the strongly erosive, coarse-grained facies of unit 2. The best outcrop occurrences of this contact are located along the Simonette River south of its confluence with the Smoky River, as well as on the north bank of the Wapiti River near its drainage into the Smoky River valley.

The lower portion of unit 2 consists of decametre-thick, fining-upward, paleochannel fills interbedded with a variety of subordinate finer grained packages representative of channel top, levee, rooted overbank, and alluvial plain paleoenvironments. Channel sandstones commonly display medium- to large-scale trough cross bedding and planar cross bedding, large wood fragments, and rounded intraclasts. Coal seams are discontinuous and probably originated as oxbow lake or abandoned channel deposits. Paleocurrent measurements from the lower deposits of unit 2 (n=128) indicate predominant flow toward northeast (N15°E). Furthermore, subsurface and outcrop data indicate that paleochannel deposits are usually isolated both laterally and vertically, and that the paleochannel-overbank ratio is near equal, thus suggesting conditions of medium to high accommodation. Bentonitic beds increase in number and thickness toward the top of the unit: in particular, a 60 cm thick altered volcanic ash referred here as Horizon A, represent an important marker bed in the study area, particularly for the identification of the upper contact of unit 2 in subsurface data. Overall, this stratigraphic unit is 100-120 m thick: however, its thickness decreases to 50–60 m along dip toward the NE (see also Fig. 5).

Wapiti Formation - unit 3

Unit 3 consists of a distinctive fining-upward succession that locally reaches a maximum thickness of 140 meters. This unit is characterized by a transition from low to high accommodation and another major shift in fluvial architecture and stacking pattern (Fig. 9). The contact with the underlying unit 2 is marked by sharp-based, massive, amalgamated channel sandstones up to 35 meters thick. The nature of the basal surface is unconformable and it can be identified in subsurface by a prominent decrease in the gamma ray response. Sandstones occur in stacked, multi-storied, fining-upward packages with sharp, erosive bases. Individual scour-based channel fills range in thickness between 2 and 10 meters. Large wood fragments, small intraclasts, and ironstone nodules are ubiquitous. These beds are devoid of coal or organic-rich mudstones. Locally, channel sandstones are interbedded with silty and muddy alluvial plain deposits which have lenticular geometries and range from 1 to 3 kilometres in widht. This facies association is interpreted to be the product of a widespread, low sinuosity fluvial system characterized by relatively shallow channels. Extensive lateral and vertical stacking of sand bodies with only sporadic fine-grained deposits suggests a low-accommodation setting. Paleocurrent measurements from trough cross-bedded sandstones indicate predominant flow toward east (N60°E). The best exposures of these amalgamated channels and the lower bounding unconformity of unit 3 are located on the eastern bank of the Smoky River, approximately 4 km south of its confluence with the Wapiti River, as well as along the Wapiti River downstream from the mouth of Bear Creek. Bedding geometry and overall depositional conditions are similar to those reported for the Comrey Member (also known as the Comrey Sandstone) of the Oldman Formation in southern Alberta (Eberth and Hamblin 1993; Hamblin 1997a).

Conformably overlying the 30-40 meter thick basal sandy member of unit 3 are fine-grained deposits which constitute the bulk of the unit (Fig. 10). In the subsurface, this stratigraphic interval is marked by a significantly higher radioactivity values along with a significant decrease in porosity. The upper portion of unit 3 consists primarily of interbedded siltstone and mudstone with minor sandstone, and extensive coal deposits. A significant reduction in the number and thickness of sandstone beds occurs along with an increase in silt and mud-dominated inclined heterolitic strata

(IHS, *sensu* Thomas et al. 1987). The IHS contain lateral and vertical accretion surfaces typical of fluvial point bars deposited in high-sinuosity channel systems. Silicified plant remains are fairly common within the silty intervals, as are ironstone lenses and nodules, and sideritic and carbonaceous concretions. Floodplain deposits are rich in organic components and contain abundant rootlets, suggesting an origin related either to neck cut-off of meander bends or to extensive bogs and marshes. Paleocurrent measurements from this upper interval (n=134) indicate predominant flows toward east, although they display a multidirectional pattern typical of meandering systems.

Coal seams are particularly well developed within this upper interval of unit 3, with individual thicknesses of up to 1.5 meters. In addition, coal beds are commonly associated with reddish, decimetre-thick peat deposits, thus indicating widespread marshy areas and associated marshland vegetation. In particular, unit 3 is characterized by three coal seams (#'s 0, 1, and 2 in ascending order) that are easily traceable in the subsurface (Figs. 9 and 10). Lastly, altered volcanic ash beds and derived bentonitic paleosols are abundant in this interval, including some that measure up to 3 meters in thickness. Such deposits are laterally extensive and useful for correlation purposes. A volcanic ash layer sampled at the Kleskun Hills Park yielded a $^{40}Ar/^{39}Ar$ age of 73.77 ± 1.46 Ma (Eberth, in Fanti 2007). Within this unit, several regionally extensive marker beds were identified both in outcrop and subsurface. For instance, two bentonite layers referred here as the Horizon B and Horizon C reach 475 and 90 cm in thickness respectively (Figs. 4, 5, and 9) and extend for more than 100 km along strike and for 90 km along dip in the study area.

Strata of unit 3 crop out extensively at the Kleskun Hill Park, near the town of Hythe, along the Bear and Spring creeks, and also along both banks of the Wapiti River south of Grande Prairie. In addition, highly weathered exposures of this interval are found in the Smoky River valley.

Unit 3 is bounded at the top by a sharp, strongly erosive unconformity that can be identified by a prominent low gamma ray signature (Fig. 9). This facies contact juxtaposes the organic mudstones of unit 3 with the coarse-grained, cross-bedded channel and crevasse splay sandstones of the overlying unit 4. Combined well-log and outcrop data indicate that the unconformable nature of this stratigraphic contact is evident toward west and south, whereas the contact becomes conformable in an east-southeast (basinward) direction.

Wapiti Formation - unit 4

Facies associations of unit 4 are dominated by fining-upward successions of levee, crevasse splay, and overbank sheetflood deposits where small-scale cross beds, planar and undulatory laminated fine to very fine sand and silt, and thin organic lamination are the typical sedimentary structures (Fig. 11A). Frequently, coal seams and light green to yellow altered volcanic ashes top the overbank deposits. The lowermost sandstone bodies are 1 to 3 meters thick with erosive bases; sedimentary structures include low-angle to horizontal lamination, trough cross-bedding, and ripple cross lamination. Small clay clasts, ironstone and bentonite lenses, and large plant remains are abundant in these beds. Sandstones interfinger locally with organic-rich mudstones and ironstone lenses (Fig. 12). A bentonite found within the most basal strata of this unit cropping out along Pipestone Creek yielded a $^{40}Ar/^{39}Ar$ age of 73.25 ± 0.25 Ma (Eberth, in Currie et al. 2008). This age is roughly equivalent to the Bearpaw – Horseshoe Canyon transition in central and southern Alberta, at approximately 73 Ma (Eberth 2005; Eberth and Deino 2005).

Above these basal deposits, individual channel fill successions increase significantly in thickness, commonly exceeding 25 meters. Coal beds are tabular, generally contain abundant rootlets near their base, and are commonly associated with dark grey, carbonaceous mudstone. In spite of thicknesses of up to 1 meter, coal seams tend to pinch out within 2 to 5 km. Channel bodies are both horizontally and vertically separated by widespread siltstone and organic-rich mudstone (floodplain deposits), and are locally interbedded with crevasse splay fine-grained sandstone and siltstone. The stratigraphic architecture has an overall aggradational pattern, and is interpreted to indicate conditions of medium to high accommodation. Paleocurrent measurements from three-dimensional exposures (n=142), as well as the orientation of vertebrate remains at different fossiliferous sites (n=102) indicate a predominantly northward flow direction (N5°E).

The upper 40 meters of unit 4 are characterized by a thick coal-bearing interval referred to as the Red Willow Coal Zone (after Dawson et al. 1994b). Within this interval, several extensive coal seams (locally up to 2 meters thick) are interbedded with carbonaceous, organic-rich mudstones, fine grained overbank and floodplain deposits, and bentonitic lenses (Fig. 11). A variety of fossils have been recovered from the mudstone deposits of this stratigraphic interval, including duck-billed and horned dinosaur remains and tracks, megaplants, and insects in amber (Tanke 2004; Fanti and Currie 2007; Currie et al. 2008). Continuous exposures of several of these coal seams are located along most of the Red Willow River (including outcrops in British Columbia), as well as along both sides of the Wapiti River, and the Beaverlodge and Calahoo creeks. Widespread coal deposition and higher water table conditions may reflect a major environmental shift in the area during the latest Campanian, and may also be associated with high-accommodation conditions and a reduction in clastic sediment supply. Based on palynological data, Dawson et al. (1994b) indicate a latest Campanian – earliest Maastrichtian age for these beds, which suggests a correlation between the Red Willow River coal deposits and the middle beds of the Brazeau Formation in the central Alberta foothills (Srivastava 1970; Jerzykiewicz and Sweet 1988; Dawson and Kalkreuth 1989; Sweet et al. 1989; Osborn 2006). Well-log data indicate that the Red Willow coal beds lie approximately 180 meters above the Pipestone Creek bentonite at the base of unit 4. Assuming an average sedimentation rate of 6 cm / 1000 yrs under medium to high accommodation conditions (Eberth and Deino 2005), the 180 meters would represent a 2.8 Ma interval. Since the Pipestone Creek bentonite yielded an age of 73.25 Ma, this would suggest that lower Red Willow coal seams were deposited at approximately 70.4 Ma. The Campanian-Maastrichtian boundary has been recently dated as 70.6 Ma by Ogg et al. (2004), and therefore this study supports the conclusion presented by Dawson et al. (1994b) regarding the age of the Red Willow coal zone. This stratigraphic interval is therefore likely to be coeval to "unit 2" of the Horseshoe Canyon Formation (Eberth 2002) and to the Drumheller Marine Tongue of central Alberta (Gibson 1977; Lerbekmo and Braman 2002; Eberth and Deino 2005). The overall thickness of unit 4, including the Red Willow interval, is approximately 200 meters.

Wapiti Formation - unit 5

Unit 5 overlies gradationally unit 4, and is characterized by near equal amounts of channel and floodplain deposits (Fig. 11B). Sandstone beds range from 10 to 100 cm in thickness, are planar in overall geometry, and fine upward into silty, organic-rich deposits. Coal lenses and extensive mud deposits are frequently interbedded with patchy ironstone beds. The alluvial deposits of this unit display a depositional architecture similar to that of unit 4, with alternating paleochannel sandstones and overbank facies within a multi-storied system. However, single channel fills are significantly smaller (2-4 meters thick) and contain predominantly siltstone and mudstone. Yellow to light green bentonite beds are recurrent, whereas coal deposits are restricted to discontinuous, centimetre- to decimetre-thick lenses. Several continuous exposures along the Red Willow and Wapiti rivers, and particularly along the Pinto Creek, permitted the collection of 103 paleocurrent measurements for this interval. The data indicate a consistent pattern toward north (N2°W) suggesting the presence of a widespread axial drainage system. Available subsurface data for unit 5 are restricted to the area south of the Wapiti River west of the Alberta Syncline axis. To the north of these boundaries, upper Wapiti deposits have been eroded entirely and bedrock is directly overlain by Quaternary deposits.

The top of unit 5, which coincides with the top of the Wapiti Formation, is characterized by a coal rich interval, referred to as the Cutbank Coal Zone (established by Dawson et al. 1994a). Blocky coal seams up to 2 meters thick crop out extensively along the Pinto Creek and the Cutbank River where they interfinger with carbonaceous mudstone, and, locally, with highly weathered bentonites. A distinctive palynological assemblage (Dawson et al. 1994b) includes several Maastrichtian taxa: *Scollardia trapaformis* and *Mancicorpus gibbus*, the zonal index species of the

M. gibbus miospore subzone of the *S. trapaformis* miospore Zone (Srivastava 1970; Braman and Sweet 1999; Eberth 2002). This zone is widely recognized in the Canadian side of the Western Interior Basin, and correlates with magnetochrons 31n and 30r (67.6 – 68 Ma in age; Lerbekmo and Braman 2002; Ogg et al. 2004; Wu et al. 2007, and references therein). Consequently, this interval correlates with "unit 5" of the Horseshoe Canyon Formation which is thought to correspond to relatively wet climatic and high accommodation conditions (Eberth 2002), and the Carbon and Thompson coal seams of the Alberta plains (Gibson 1977; McCabe et al. 1989). Concurrent deposition of the Cutbank Coal Zone (Wapiti Formation), Whitemud and Battle formations across much of central Alberta and Saskatchewan, and the coaly deposits of "unit 5" of the Horseshoe Canyon Formation in central Alberta may indicate a regional decrease in sediment supply and a relative rising of the water table.

Wapiti – Scollard Formation transition

The lower boundary of the Scollard Formation is marked by an unconformable, sharp contact at the base of massive, coarse-grained amalgamated sandstones (Fig. 13). This boundary, which juxtaposes fine mudstone and clay of the Cutbank Coal Zone with the paleochannel sheet sandstones of the Entrance Member (Fig. 11), is a widespread, regionally mappable unconformity which is well represented in both subsurface and outcrop data (Jerzykiewicz and McLean 1980; Jerzykiewicz 1985; Dawson et al. 1994b). Paleocurrent measurements display an almost unidirectional east-west pattern (N70°E) that strongly differs from the south-north trend observed in the underlying beds of unit 5. The most continuous exposures of this contact crop out in the Cutbank River valley and in several roadcuts along Highway 40 between Grande Prairie and Grande Cache.

Significance of marker beds and stratigraphic unconformities

The stratigraphic units identified in the Wapiti Formation document changes in channel stacking pattern, channel to overbank ratios, and occurrence of coal and other organic-rich deposits. Such variations likely resulted from major changes in accommodation and sediment supply during the deposition of the Wapiti Formation.

Most unit boundaries are represented by regionally mappable unconformities that commonly juxtapose fine, low-energy type of deposits with medium- and coarse-grained strata indicative of sedimentation under high-energy conditions. These subaerial unconformities occur (in ascending order) at the tops of units 1, 2, 3, and 5. The character of these contacts has been documented in both subsurface and outcrop (Figs. 4 and 5). Their correlation with the better known stratigraphic units of central Alberta has become apparent based on the chronostratigraphic framework afforded by radioisotopic, magnetostratigraphic, and biostratigraphic data. Such methodologies offer the best opportunity for the basin-scale correlation of the proposed stratigraphic subdivisions (units 1 to 5 in this paper) of the Wapiti Formation.

The Wapiti Formation also contains numerous regionally mappable marker beds, in particular coal seams, coaly intervals, and bentonites. Among the coal beds, the basal coal layer and the overlying coal-rich deposits of unit 1, the coal beds 0, 1, and 2 in the fine-grained strata of unit 3, and the Red Willow and Cutbank coal zones of units 4 and 5 respectively, are potentially useful for intraformational correlation (Fig. 5).

Three meter-thick bentonites display a uniform and continuous distribution over much of the study area, and therefore they are also useful marker beds for regional correlation. In ascending order, these bentonites are known as Horizon A (upper unit 2), Horizon B (basal unit 3), and Horizon C (uppermost unit 3). Such layers are easily identifiable in outcrop and, because of their higher radioactivity, in subsurface gamma-ray log responses as well (Figs. 4 and 5).

Petrography

The Late Campanian to Early Paleocene sandstones of the Alberta foothills were derived mostly from three types of rock: 1. intermediate acidic and basaltic volcanic rocks; 2. low-grade metamorphic rocks; and 3. sedimentary (predominantly pelitic) rocks (Lerbeckmo 1963; Dodson 1971; Rahmani and Sweet 1975; Mack and Jerzykiewicz 1989; Eberth and Hamblin 1993; McKay et al. 1995). Accordingly, the Wapiti sandstones consist largely of andesitic volcanic fragments, quartz, feldspars, and sporadic metamorphic clasts. Basic volcanic lithoclasts are as frequent as their acidic counterparts, whereas in central and southern Alberta sediments they are commonly rare or absent (Eberth and Hamblin 1993; Eberth 2005). In thin section, large and unaltered feldspar crystals (both alkali feldspar and plagioclase) are very abundant. Oxides are relatively rare, commonly forming hematitic granules or diagenetic, inter-granular cement. Extraformational granules, pebbles, and cobbles are rare, localized in thin lenses or interbedded with sandstones.

Pending further detailed petrographic studies, the most likely source of sediments for the Wapiti Formation are the Late Cretaceous volcanic complexes in the Canadian Cordillera and the Rocky Mountain Morphogeographical Belt (*sensu* Monger et al. 1982; see also Lerbeckmo 1963; Carrigy 1971; Mack and Jerzykiewicz 1988). Based on the paleocurrent measurements reported herein, as well as based on the proposed northwest – southeast drainage systems of Eberth and

Hamblin (1993) and Eberth (2005), a minor contribution from the Omineca Belt may also be inferred. The latter is considered the principal source of sediments for the Campanian successions in central and southern Alberta (Williams and Burk 1964; Rahmani and Lerbeckmo 1975; Monger et al. 1988; Eberth and Hamblin 1993).

Conclusions

Outcrop and subsurface data from the Grande Prairie region indicate that the non-marine Wapiti Formation can be subdivided into five distinctive stratigraphic units. Their description and definition have been primarily based on outcrop facies analysis, well-log correlations and interpretations, and fossil associations. Such units are separated by either conformable facies contacts (i.e., the transition from the marine Puskwaskau Formation to the fluvial deposits of unit 1; the Red Willow coal zone that separates units 4 and 5) or by subaerial unconformities of undetermined duration (i.e., the upper contacts of units 1, 2, 3, and 5). Measured sections combined with subsurface data from exploration boreholes provide a robust stratigraphic control for each unit as well as for unit boundaries and major marker beds.

Unit 1 marks the transition from the underlying marine facies of the Puskwaskau Formation to the Wapiti fluvial facies, and consists of progradational and aggradational deposits. Units 2 and 3 consist of massive and amalgamated channel-fill deposits at the base (interpreted as a low-accommodation setting), which grade upwards into more floodplain-dominated successions (interpreted as a high-accommodation setting). Significantly, unit 3 is interpreted as the inland fluvial expression of the Bearpaw transgressive event at approximately 75-73 Ma. In particular, preliminary results indicate that the maximum flooding surface of the Bearpaw seaway lies within fine sediments of upper unit 3. Unit 4 is dominated by channel sediments and extensive overbank facies, indicating accumulation under high-accommodation conditions and an overall trend of vertical aggradation. Furthermore, this unit is capped by the Red Willow Coal zone that is age-equivalent to the Drumheller Marine Tongue transgressive event as well as to the Campanian-Maastrichtian boundary (70.6 Ma; Ogg et al. 2004). Lastly, unit 5 consist of small channel deposits, crevasse and overbank facies that accumulated under medium- to high-accommodation conditions. The Cutbank Coal zone marks the top of unit 5 and is considered coeval to the Whitemud and Battle formations as well as to the Carbon and Thompson coal zones in the Alberta plains.

Data presented in this study indicate that sediment supply, accommodation, and the orientation of the major drainage systems were subject to significant variations during the deposition of the Wapiti Formation. Further studies on faunal assemblages, palynology, paleosols and coal beds will test the extent of climatic influence during the deposition of the Wapiti Formation.

Acknowledgements

We thank the Paleontological Society of The Peace and the Grande Prairie Regional College for their support in the field. R. Bickle, L. Hodges, and J. Parker provided jet boats for field work. Also, thanks to R. McRae and L. Buckley for their help and for sharing unpublished data while working in British Columbia. Comments from J. Greenough, D. Lavoie, G. Plint and an anonymous reviewer greatly improved this manuscript. We thank G.B. Vai, G.G. Zuffa (University of Bologna), A. Mumpy, E. Koppelhus (Universiy of Alberta), D. Eberth, and D. Braman (Royal Tyrrell Museum of Paleontology) for constructive criticism and numerous helpful comments.

F.F. wishes to acknowledge S. Graber, R. Hunt, K. and N. Ormay, D. Mittra, M. Paslawsky, and W. Paszkowski

Funding to F.F. was provided by the Jurassic Foundation, the Dinosaur Research Institute, the Fondazione Cassa di Risparmio in Bologna, the Bologna University and the Museum of Geology and Paleontology Giovanni Capellini (Bologna). O.C. acknowledges research support from the Natural Sciences and Engineering Research Council of Canada, as well as from the University of Alberta.

References

Allan, J., Rutherford, R., 1934. Geology of Central Alberta. Research Council of Alberta Report 30, 3 pp.

Allan, J., Carr, J. 1946. Geology and coal occurrences of Wapiti-Cutbank area, Alberta. Research Council of Alberta Report 48, 50 pp.

Bachu, S., Michael, K. 2003. Possible controls of hydrogeological and stress regimes on the producibility of coalbed methane in upper Cretaceous – Tertiary strata of the Alberta Basin, Canada. AAPG Bulletin, **87**: 1729-1754.

Bates, R., Jackson, J. 1987. Glossary of Geology, Third Edition. American Geological Institute Alexandria, Virginia, 788 pp.

Beaton, A., Langerberg, W., Pana, C. 2006. Coalbed methane resources and reservoir characteristics from the Alberta Plains, Canada. International Journal of Coal Geology, **65**: 93-113.

Byrne, P. 1955. Bentonite in Alberta. Research Council of Alberta Report 71, 17 pp.

Braman, D., Hills, L. 1990. Overview of Campanian to Paleocene stratigraphy, southern Alberta foothills. *In* Field guide to uppermost Cretaceous-Tertiary strata in southern Saskatchewan and Alberta. *Edited by* D. Braman and A. Sweet. Canadian Society of Petroleum Geologists 1990 Annual Convention, Basin Perspectives, Calgary, Alberta, pp. 53-57.

Braman, D., Sweet, A. 1999. Terrestrial palynomorph biostratigraphy of the Cypress Hills, Wood Mountain, and Turtle Mountain areas (Upper Cretaceous-Paleocene) of western Canada. Canadian Journal of Earth Sciences, **36**: 725-741.

Braunberger, W., Hall, R. 2001. Ammonoid faunas from the Cardium Formation (Turonian-Coniacian, Upper Cretaceous) and contiguous units, Alberta, Canada. I. Scaphitidae. Canadian Journal of Earth Science, **38**: 333-346.

Bridge, J., Tye, R. 2000. Interpreting the dimensions of ancient fluvial channel bars, channels, and channel belts from wireline-logs and cores. AAPG Bulletin, **84:** 1205-1228.

Brinkman, D., 2003. A review of non-marine turtles from the late Cretaceous of Alberta. Canadian Journal of Earth Sciences, **40**: 557-571.

Brinkman, D., Ryan, M., Eberth, D. 1998. The paleogeographic and stratigraphic distribution of Ceratopsid (Ornithischia) in the Upper Judith River Group of Western Canada. Palaios, **13**: 160-169.

Bustin, M., Smith, G. 1993. Coal deposits in the front ranges and foothills of the Canadian

Rocky Mountains, southern Canadian Cordillera. International Journal of Coal Geology, **23**: 1–27.

Cant, D. 1988. Regional structure and development of the Peace River Arch, Alberta: a Paleozoic failed-rift system? Bulletin of Canadian Petroleum Geology, **36**: 284-295.

Carrigy, M. 1971. Lithostratigraphy of the uppermost Cretaceous (Lance) and Paleocene strata of the Alberta Plains. Research Council of Alberta Bulletin 27.

Catuneanu, O., Sweet, A. 1999. Maastrichtian-Paleocene foreland-basin stratigraphies, western Canada: a reciprocal sequence architecture. Canadian Journal of Earth Sciences, **36**: 685-703.

Catuneanu, O., Sweet, A., Miall, A. 2000. Reciprocal stratigraphy of the Campanian – Paleocene Western Interior of North America. Sedimentary Geology, **134**: 235-255.

Catuneanu, O., Abreu, V., Bhattacharya, J., Blum, M., Dalrymple, R., Ericksson, P., Fielding, C., Fisher, W., Galloway, W., Gibling, M., Giles, K., Holbrook, J., Jordan, R., Kendall, C., Macurda, B., Martinsen, O., Miall, A., Neal, J., Nummendal, D., Pomar, L., Posamentier, H., Pratt, B., Sarg, J., Shanley, K., Steel, R., Strasser, A., Tucker, M., and Winker, C. 2009. Towards the standardization of sequence stratigraphy. Earth-Science Reviews, **92**: 1-33.

Chen, D., Bergman, K. 1999. Stratal reorientation, depositional processes, and sequence evolution of the Cretaceous in the Peace River Arch region of the Western Canada Sedimentary Basin. Bulletin of Canadian Petroleum Geology, **47**: 594-620.

Chu, M. 1978. Geology and coal resources of the Wapiti Formation of north central Alberta. Alberta Research Council Report 1978-12, 25 pp.

Cobban, W., Dyman, T., Porter, K. 2005. Paleontology and stratigraphy of upper Coniacian–middle Santonian ammonite zones and application to erosion surfaces and marine trangressive strata in Montana and Alberta. Cretaceous Research, **26**: 429-449.

Collom, C. 2001. Systematic paleontology, biostratigraphy, and paleoenvironmental analysis of the Upper Cretaceous Wapiabi Formation and equivalents; Alberta and British Columbia, Western Canada. Unpublished Ph.D. thesis, University of Calgary, Calgary, Alberta, 558 pp.

Currie, P., Langston, W., Tanke, D. 2008. A New Horned Dinosaur from an Upper Cretaceous Bonebed in Alberta. National Engineering Council Research Press, Ottawa. 152 pp.

Dawson, G. 1881. Report on an exploration from Port Simpson on the Pacific Coast to Edmonton in the Saskatchewan, embracing a portion of the northern part of British Columbia and the Peace River country. Geological survey of Canada, Report of Progress 1879-89, Part B.

Dawson, F., Kalkreuth, W. 1989. Preliminary results of a continuing study of the stratigraphic context, distribution and characteristics of coals in the Upper Cretaceous to Paleocene Wapiti Formation, northwestern Alberta. Contribution to Canadian coal Geosciences, Geological Survey of Canada, Paper 89-8, pp. 43-48.

Dawson, F., Evans, C., Marsh, R., Richardson, R. 1994a. Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin. *In* Geological Atlas of the Western Canada Sedimentary Basin. *Edited by* G. Mossop and I. Shetson. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, chapter 24, 18 pp.

Dawson, F., Kalkreuth, W., Sweet, A. 1994b. Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta. Geological Survey of Canada Bulletin, **466**: 60 pp.

Dodson, P. 1971. Sedimentology and taphonomy of the Oldman Formation (Campanian), Dinosaur Provincial Park, Alberta (Canada). Palaeogeography, Palaeoclimatology, Palaeoecology, **10**: 21-74.

Eberth, D. 1990. Stratigraphy and sedimentology of vertebrate microfossil sites in the uppermost Judith River Formation (Campanian), Dinosaur Provincial Park, Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology, **78**: 1-36.

Eberth, D. 2002. Review and comparison of Belly River Group and Edmonton Group stratigraphy and stratigraphic architecture in the southern Alberta plains. Canadian Society of Petroleum Geologists, Diamond Jubilee Convention, Program and Abstract 117. Abstracts of Technical Talks, Poster and Core Displays including Extended abstracts. PDF file 227S0125 CD.

Eberth, D. 2005. The geology. *In* Dinosaur Provincial Park, a spectacular ecosystem revealed. *Edited by* P. Currie and E. Koppelhus. Indiana university Press, Bloomington, chapter 3, pp. 54-82.

Eberth, D., Hamblin, A. 1993. Tectonic, stratigraphy, and sedimentologic significance of a regional discontinuity in the upper Judith River Group (Belly River wedge) of southern Alberta, Saskatchewan, and northern Montana. Canadian Journal of Earth Sciences, **30**: 174-200.

Eberth, D., Brinkman, D. 1997. Paleoecology of an estuarine, incised valley fill in the Dinosaur Park Formation (Judith River Group, Upper Cretaceous) of southern Alberta, Canada. Palaios, **12**: 43-58.

Eberth, D., Deino, A. 2005. New $^{40}Ar/^{39}Ar$ ages from three bentonites in the Bearpaw, Horseshoe Canyon, and Scollard formations (Upper Cretaceous-Paleocene) of southern Alberta. *In* Dinosaur Park Symposium - Short Papers, Abstracts and Program. *Edited by* D. Braman, F. Therrien, E. Koppelhus and W. Taylor. Special Publication of the Royal Tyrrell Museum, pp. 23-24.

Evans, C., Caley, J. 1929. Reconnaissance survey of foothill are in Wapiti River basin, Alberta. Canada Department of Mines Geological Survey, Summary Report Part B 2255, 4 pp.

Fanti, F., Currie, P. 2007. A new *Pachyrhinosurus* bonebed from the late Cretaceous Wapiti Formation. *In* Dinosaur Park Symposium - Short Papers, Abstracts and Program. *Edited by* D. Braman, F. Therrien, E. Koppelhus and W. Taylor. Special Publication of the Royal Tyrrell Museum, pp. 39-43.

Fanti, F., Miyashita, T. An high latitude vertebrate fossil assemblage from the Late Cretaceous of North Western Alberta, Canada: evidences for dinosaur nesting and vertebrate latitudinal gradient. In press, Palaeogeography, Palaeoclimatology, Palaeoecology.

Fiorillo, A., Gangloff, R. 2003. Preliminary notes on the taphonomic and paleoecologic setting of a *Pachyrhinosaurus* bonebed in northern Alaska. Journal of Vertebrate Paleontology, **23**: 50A.

Gibson, D. 1977. Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller- Ardley region, Red Deer River Valley, Alberta. Geological Society of Canada, Paper 76-35, 41 pp.

Gleddie, J. 1949. Upper Cretaceous in Western Peace River Plains, Alberta. Bulletin of the American Association of Petroleum Geologists, **33**: 511-532.

Green, R. 1972. Geological Map of Alberta. Alberta Research Council, Edmonton, Alberta, Scale 1:1 267 000

Hackbarth, D. 1976. Hydrogeology of the Grande Prairie area, Alberta. Alberta Research Council Report 76-4, 17 pp.

Hamblin, A. 1997a. Stratigraphic architecture of the Oldman Formation, Belly River Group, surface and subsurface of southern Alberta. Bulletin of Canadian Petroleum Geology, **45**: 155-177.

Hamblin, A., Abrahamson, B. 1996. Stratigraphic architecture of “Basal Belly River” cycles, Foremost Formation, Belly River Group, subsurface of southern Alberta and southwestern Saskatchewan. Bulletin of Canadian Petroleum Geology, **44**: 654- 673.

Hu, Y. 1997. High-resolution sequence stratigraphic analysis of the Upper Cretaceous Puskwaskau Formation of west-central Alberta and adjacent British Columbia: outcrop and subsurface. Ph.D. thesis, the university of Western Ontario, London, Ontario, 310 pp.

Irish, E. 1970. The Edmonton Group of south-central Alberta. Bulletin of Canadian Petroleum Geology, **18**: 125-155.

Kauffman, E., Caldwell, W. 1993. The Western Interior Basin in Space and Time. *In* Evolution of the Western Interior Basin. *Edited by* W. Caldwell and E. Kauffman. Geological Association of Canada Special Paper 39, 1-30.

Kramers, J., Mellon, G. 1972. Upper Cretaceous-Paleocene coal-bearing strata, northwest-central Alberta plains. *In* Proceeding of the first Geological Conference on Western Canadian Coal. Research Council of Alberta. *Edited by* G. Mellon, J. Kramer, and E. Seagel. Report 60, pp. 109-124.

Jerzykiewicz, T. 1985. Stratigraphy of the Saunders Group in the central Alberta Foothills - a progress report. Geological Survey of Canada, Current Research, Part B, Paper 85-1B, 247-258.

Jerzykiewicz, T., McLean, J. 1980. Lithostratigraphical and sedimentological framework of coal-bearing Upper Cretaceous and lower Tertiary strata, Coal Valley Area, Central Alberta Foothills. Geological Survey of Canada, Paper 79-12, 47 pp.

Jerzykiewicz, T., Sweet, A. 1988. Sedimentological and palynological evidence of regional climatic changes in Campanian to Paleocene sediments of the Rocky Mountain Foothills, Canada. Sedimentary Geology, **59**: 29-76.

Jerzykiewicz, T., Norris, D. 1994. Stratigraphy, structure and syntectonic sedimentation of the Campanian "Belly River" clastic wedge in the southern Canadian Cordillera. Cretaceous Research, **15**: 367-399.

Langston, W. 1967. The thick-headed ceratopsian dinosaur *Pachyrhinosauru*s (Reptilia: Ornithischia), from the Edmonton Formation near Drumheller, Canada. Canadian Journal of Earth Sciences, **4**: 171-186.

Langston, W. 1975. The ceratopsian dinosaurs and associated lower vertebrates from the St. Mary River Formation (Maestrichtian) at Scabby Butte, southern Alberta. Canadian Journal of Earth Sciences, **12**: 1576-1608.

Lerbeckmo, J. 1963. Petrology of the Belly River Formation, southern Alberta Foothills. Sedimentology, **2**: 54-86.

Leckie, D., Bhattacharya, J., Bloch, J., Gilboy, C., Norris, B. 1994. Cretaceous Colorado / Alberta Group of the Western Canada Sedimentary Basin. *In* Geological Atlas of the Western Canada Sedimentary Basin. *Edited by* G. Mossop and I. Shetson. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, chapter 20, 15 pp.

Lerbeckmo, J., Braman, D. 2002. Magnetostratigraphic and biostratigraphic correlation of late Campanian and Maastrichtian marine and continental strata from the Red Deer Valley to the Cypress hill, Alberta, Canada. Canadian Journal of Earth Sciences, **39**: 539-557.

Lerbeckmo, J., Braman, D., Catuneanu, O., Humprey, N. 2003. Magnetostratigraphic and palynostratigraphic correlation of late Campanian strata of the Bearpaw and Horseshoe Canyon formations of the RCA Castor corehole to the Red Deer Valley, Alberta. Bulletin of Canadian Petroleum Geology, **51**: 70-77.

Macdonald, D., Ross, T., McCabe, P., Bosman, A. 1987. An evaluation of the coal resources of the Belly River Group, to a depth of 400 m in the Alberta Plains. Alberta Geological Survey, Open File Report 1987-8, pp. 76.

MacEachern J., Hobbs, T. 2004. The ichnological expression of marine and marginal marine conglomerates and conglomeratic intervals, Cretaceous Western Interior Seaway, Alberta and northeastern British Columbia. Bulletin of Canadian Petroleum Geology, **52**: 77-104.

Mack, G., Jerzykiewicz, T. 1989. Provenance of post-Wapiabi sandstones and its implications for Campanian to Paleocene tectonic history of the southern Canadian Cordillera. Canadian Journal of Earth Sciences, **26**: 665-676.

McCabe, P., Strobl, R., Macdonald, D., Nurkowski, J., Bosman, A. 1989. An evaluation of the coal resources of the Horseshoe Canyon Formation and laterally equivalent strata to a depth of 400 meters, in the Alberta plains area. Alberta Research Council, Open File Report 1987-07.

McKay, J., Longstaffe, F., Plint, A. 1995. Early diagenesis and its relationship to depositional environment and relative sea-level fluctuations (Upper Cretaceous Marshybank Formation, Alberta and British Columbia). Sedimentology, **42**: 161- 190.

McNeil, D., Caldwell, W. 1981. Cretaceous rocks and their foraminifera in the Manitoba Escarpment. Geological Association of Canada Special Paper 21, 439 pp.

McMechan, M., Dawson, F. 1995. Geology, Wapiti, West of Sixth Meridian, Alberta Geological Survey of Canada, Series Map1875A, 1: 250000.

Monger, J., Price, R., Wanless, R. 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic belts in the Canadian Cordillera. Geology, **10**: 70-75.

Nielsen, K., Schroder-Adams, C., Leckie, D. 2003. A new stratigraphic framework fort he Upper Colorado Group (Cretaceous) in southern Alberta and south-western Saskatchewan, Canada. Bulletin of Canadian Petroleum Geology, **51**: 304-346.

O'Connel, S., Dix, G., Barclay, J., 1990. The origin, history and regional structural development of the Peace River Arch, western Canada. Bulletin of Canadian Petroleum Geology, **38**: 4-24.

Obradovich, J. 1993. A Cretaceous time-scale. In: Caldwell, W., and Kauffman, E. (Eds), Evolution of the Western Interior Basin. Geological Association of Canada Special Paper, **39**: 379-396.

Obradovich, J., Cobban, W. 1975. A time-scale for the Late Cretaceous of the Western Interior of North America. *In* The Cretaceous system in the Western Interior of North America. *Edited by* W. Caldwell. The Geological Association of Canada Special Paper 13, 31-54.

Ogg, J., Agterberg, F., Gradstein, F. 2004. The Cretaceous Period. *In* A Geologic time scale. *Edited by* F. Gradstein and J. Ogg. Cambridge University Press, Cambridge, 344-383.

Osborn, G., Stockmal, G., 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, **75.** 450-477.

Plint, A., Norris, B., Donaldson, W. 1990. Revised definitions for the Upper Cretaceous Bad Heart Formation and associated units in the foothills and plains of Alberta and British Columbia. Bulletin of Canadian Petroleum Geology, **38**: 78-88.

Porter, J., Price, R., McCrossan, R. 1982. The Western Canada Sedimentary Basin. Philosophical Transactions of the Royal Society of London, A305, 1489, 169-193.

Power, B., Walker, R. 1996. Allostratigraphy of the Upper Cretaceous Lea Park-Belly River transition in central Alberta, Canada. Bulletin of Canadian Petroleum Geology, **44**: 14-38.

Rahmani, R., Lerbekmo, J. 1975. Heavy-mineral analysis of Upper Cretaceous and Paleocene sandstones in Alberta and adjacent areas of Saskatchewan. *In* The Cretaceous system in the Western Interior of North America. *Edited by* W. Caldwell. The Geological Association of Canada Special Paper 13, 607-632.

Rosental, L., Walker, R. 1987. Lateral and vertical facies sequences in the Upper Cretaceous Chungo Member, Wapiabi Formation, southern Alberta. Canadian Journal of Earth Sciences, **24**: 771-783.

Ryan, B. 1989. Preliminary survey if the coal resources of Upper Cretaceous rocks, northeastern British Columbia. Geological Fieldwork 1989, B.C. Ministry of Energy, Mines and Petroleum Resources, Paper 1990-1, 469- 471.

Rutherford, R. 1930. Geology and Water Resources in Parts of the Peace River and Grande Prairie Districts, Alberta. Alberta Geological Survey Report, **21**: 30 pp.

Selwin, A. 1874. Geological Survey of Canada, Report of Progresses 1873-1874.

Smith, G., Cameron, A., Bustin, R. 1994. Coal Resources of the Werstern Canada Sedimentary Basin. *In* Geological Atlas of the Western Canada Sedimentary Basin. *Edited by* G. Mossop and I. Shetson. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, chapter. 33, 20 pp.

Srivastava, S. 1970. Pollen biostratigraphy and paleoecology of the Edmonton Formation

(Maestrichtian), Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology, **7**: 221-276.

Stancliffe, R., McIntyre, D. 2003. Stratigraphy and palynology of the Cretaceous Colorado Group and Lea Park Formation at Cold Lake, Alberta, Canada. Bulletin of Canadian Petroleum Geology, **51**: 91-98.

Stelck, C. 1975. Basement control of Cretaceous sand sequences in Western Canada. *In* The Cretaceous system in the Western Interior of North America. *Edited by* W. Caldwell. The Geological Association of Canada Special Paper 13, 427-440.

Sternberg, C. 1950. *Pachyrhinosaurus canadensis*, representing a new family of the Ceratopsia, from southern Alberta. Canada Natural Museum Bulletin, **118**: 109-120.

Stott, D. 1961. Dawson Creek map area, British Columbia. Geological Survey of Canada, Paper 61-10.

Stott, F. 1963. The Cretaceous Alberta Group and equivalent rocks, Rocky Mountain Foothills, Alberta. Geological Survey of Canada, Memoir 317, 306 pp.

Stott, D. 1967. The Cretaceous Smoky Group. Rocky Mountain Foothills. Alberta and British Columbia. Geological Survey of Canada. Bulletin, **132**: 133 pp.

Sweet, A. and Braman, D. 1990. Age and stratigraphic significance of the Wapiabi-Brazeau transition, south-central Alberta Foothills and Plains. *In* Field guide to uppermost Cretaceous-Tertiary strata in southern Saskatchewan and Alberta. *Edited by* D. Braman and A.Sweet. Canadian Society of Petroleum Geologists, Convention, Basin Perspectives, Calgary, Alberta. pp. 15-22.

Sweet, A., Ricketts, B., Cameron, A., Norris, D. 1989. An integrated analysis of the Brackett coal basin, Northwest Territories. Geological Survey of Canada, Paper 89-1, 85-89.

Tanke, D. 2004. Mosquitoes and mud – The 2003 Royal Tyrrell Museum of Paleontology expedition to the Grande Prairie region (north-western Alberta, Canada). Alberta Paleontological Society Bulletin, **19**: 3-31.

Thomas, R., Smith, D., Wood, J., Visser, J., Calverley-Range, E., Koster, E. 1987. Inclined heterolitic stratification – terminology, description, interpretation and significance. Sedimentary Geology, **53**: 123-179.

Varban, B., Plint, G. 2008. Sequence stacking patterns in the Western Canada foredeep: influence of tectonics, sediment loading and eustasy on deposition of the Upper Cretaceous Kaskapau and Cardium formations. Sedimentology, **55**: 395-421.

Williams, G., Burk, C. 1964. Upper Cretaceous. *In* Geological history of western Canada.

Edited by R. McGrossan and R. Glaister. Alberta Cociety of Petroleum Geologists, Calgary, pp. 169-189.

Wu, X., Brinkman, D., Eberth, D., Braman, D. 2007. A new ceratopsid dinosaur (Ornithischia) from the uppermost Horseshoe Canyon Formation (upper Maastrichtian), Alberta, Canada. Canadian Journal of Earth Sciences, **44**: 1243-1265.

Figure Caption

Figure 1: Stratigraphic nomenclature for the Upper Cretaceous of Alberta showing the proposed subdivision of the Wapiti Formation into five stratigraphic units.

Figure 2: Geographic distribution of the Wapiti Formation outcrops in the Grande Prairie area and western British Columbia. Black dots indicate locations of well logs used in this study.

Figure 3: Location map of the Grande Prairie area showing positions of studied subsurface sections. Well-log (primarily gamma ray) cross sections are SW-NE dip-oriented and NW-SE strike-oriented.

Figure 4: Gamma-ray stratigraphic cross sections illustrating the Puskwaskau to Wapiti transition. Datum 1 is a marker bentonite within the marine shale of the Puskwaksau Formation that crops out extensively on both flanks of the Smoky River north of Grande Prairie. Maximum Flooding Surfaces (MFS) and flooding surfaces (FS) in the Puswkaskau Formation were identified combining field observation and gamma ray response. The basal fluvial deposits of the Wapiti Formation are characterized by frequent and widespread coal seams, referred here as the Basal Coal Zone.

Figure 5: Gamma-ray SW-NE dip-oriented (D-D') and NW-SE strike-oriented (T-T') stratigraphic sections showing major marker beds and unit contacts of uppermost Puskwaskau Formation and unit 1 to 3 of the Wapiti Formation.

Figure 6: A, detailed structure map of the basal contact of the Wapiti Formation in the Grande Prairie region based on data from 550 well logs. Depth in meters. B, isopach map of the Wapiti Formation showing total thickness in the study area. To the south, the Wapiti is capped by the Scollard Formation. Thickness in meters. C, simplified cross-section of the Alberta basin showing the near vertical strata orientation in concomitance with the present day deformation front (modified after Green 1972).

Figure 7: Combined outcrop and gamma-ray log showing the transition from the Puskwaskau Formation and the Wapiti Formation (Belcourt Creek, B.C.). The base of the Wapiti Formation (i.e., base of unit 1) is placed at the occurrence of the first laterally persistent coal seam. Log scale in meters. Reference log from well 07-27-068-11W6/0.

Figure 8: A, Combined gamma-ray log, lithostratigraphy and facies description of the uppermost Puskwaskau Formation and Wapiti unit 1. Note the occurrence of coal seams in the lower section of unit 1 as well as the abrupt leftward deflection of the gamma-ray signal at the base of unit 2. B, Combined gamma-ray and lithostratigraphic logs of Wapiti unit 2. Paleocurrent directions are represented by rose diagrams. 1. Puskwaskau Formation, Belcourt Creek (B.C.); 2. floodplain

deposits of unit 1, Wapiti River (B.C.); 3, coarse grained deposits within channel deposits of unit 1, White Mountain (Grande Prairie); 4, massive and amalgamated sandstones of basal unit 2 overlying organic-rich, fine grained beds of unit 1, Simonette River (Grande Prairie); 5, channel deposits in the upper unit 2 showing a progressive reduction in available accommodation, Smoky River valley (Grande Prairie); 6, amalgamated channel sandstone of basal unit 3, Red Willow River (Grande Prairie).

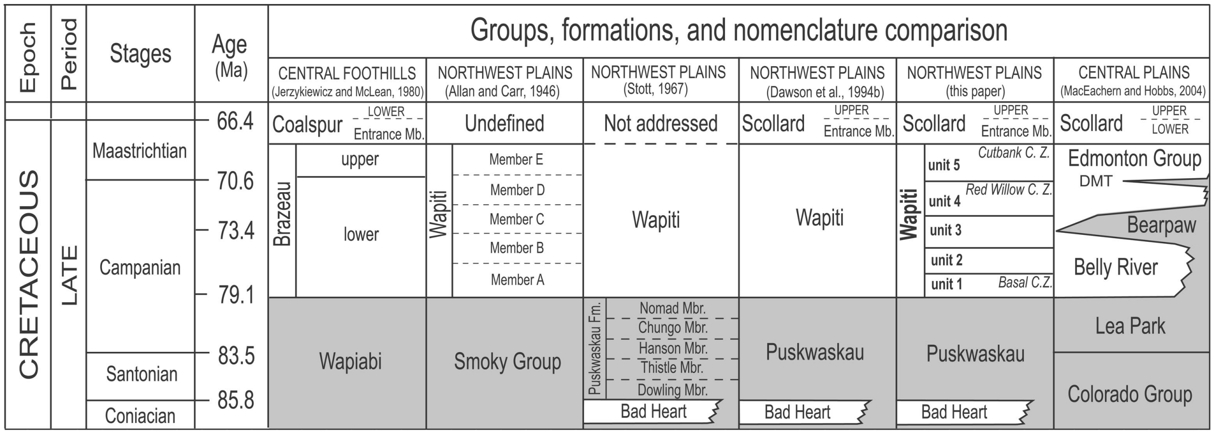
Figure 9: Combined gamma-ray and lithostratigraphic logs of Wapiti unit 3. Note the prominent rightward shift of the gamma-ray signal and the overall fining upward trend. 1. massive and amalgamated channel deposits marking the transition from unit 2 to unit 3, Wapiti River (Grande Prairie); 2, fine grained Inclined Heterolitic Stata (*sensu* Thomas et al. 1987) overlaid by tabular peat and coal, Kleskun Hill Park (Grande Prairie); 3, IHS overlaid by peat and coal tabular seams Kleskun Hill Park (Grande Prairie).

Figure 10: Lithostratigraphic log of unit 3 beds exposed at the Kleskun Hill Park (Grande Prairie). This unit is characterized by the nearly absence of sand, widespread coal seams, and an overall increase in accommodation.

Figure 11: A, combined gamma-ray and lithostratigraphic logs of Wapiti unit 4. The base of the unit is marked by an abrupt leftward gamma-ray signal deflection. Note the Red Willow coal zone in the uppermost 40 meters of unit 4. B, combined gamma-ray and lithostratigraphic logs of Wapiti unit 5. The basal contact of unit 5 is placed on top of the last laterally persistent coal seam of the Red Willow c.z., whereas the upper one is marked by the abrupt contact with the coarse grained deoposits of the Entrance Member (lower Scollard Formation). Coals at the top of unit 5 form the Cutbank Coal Zone. 1. complete channel fill sequences along the Red Willow River suggesting a deposition in medium to high accommodation conditions; 2. tabular coal seam in the Red Willow Coal Zone (Red Willow River); 3. channel base sandstones, Red Willow River (Grande Prairie); 4. tabular, meter-thick coal seams of the Cutbank Coal Zone, Pinto Creek (Grande Prairie).

Figure 12: A, detailed stratigraphic section of unit 4 exposures at the Pipestone Creek; B, interbedded channel sandstones and floodplain deposits of basal unit 4 exposed at the merge between the Pipestone Creek and the Wapiti River; C, detail of sedimentary structures in the channel sandstones.

Figure 13: A, outcrop of the Entrance Member (lower Scollard Formation-lower Coalspur Formation) along the Highway 40 South, Smoky River Valley approximately 100 km south of Grande Prairie. B, lower beds of the Scollard-Coalspur Formation near Grande Cache (Highway 40 South).



Epoch
Period
Stages
Age (Ma)
Groups, formations, and nomenclature comparison
CENTRAL FOOTHILLS (Jerzykiewicz and McLean, 1980)
NORTHWEST PLAINS (Allan and Carr, 1946)
NORTHWEST PLAINS (Stott, 1967)
NORTHWEST PLAINS (Dawson et al., 1994b)
NORTHWEST PLAINS (this paper)
CENTRAL PLAINS (MacEachern and Hobbs, 2004)
CRETACEOUS
LATE
Maastrichtian
Campanian
Santonian
Coniacian
66.4
70.6
73.4
79.1
83.5
85.8
Coalspur
LOWER
Entrance Mb.
Brazeau
upper
lower
Wapiabi
Undefined
Wapiti
Member E
Member D
Member C
Member B
Member A
Smoky Group
Not addressed
Wapiti
Puskwaskau Fm.
Nomad Mbr.
Chungo Mbr.
Hanson Mbr.
Thistle Mbr.
Dowling Mbr.
Bad Heart
Scollard
UPPER
Entrance Mb.
Wapiti
Puskwaskau
Bad Heart
Scollard
UPPER
Entrance Mb.
Wapiti
unit 5
Cutbank C. Z.
unit 4
Red Willow C. Z.
unit 3
unit 2
unit 1
Basal C.Z.
Puskwaskau
Bad Heart
Scollard
UPPER
LOWER
Edmonton Group
DMT
Bearpaw
Belly River
Lea Park
Colorado Group

Figure 1

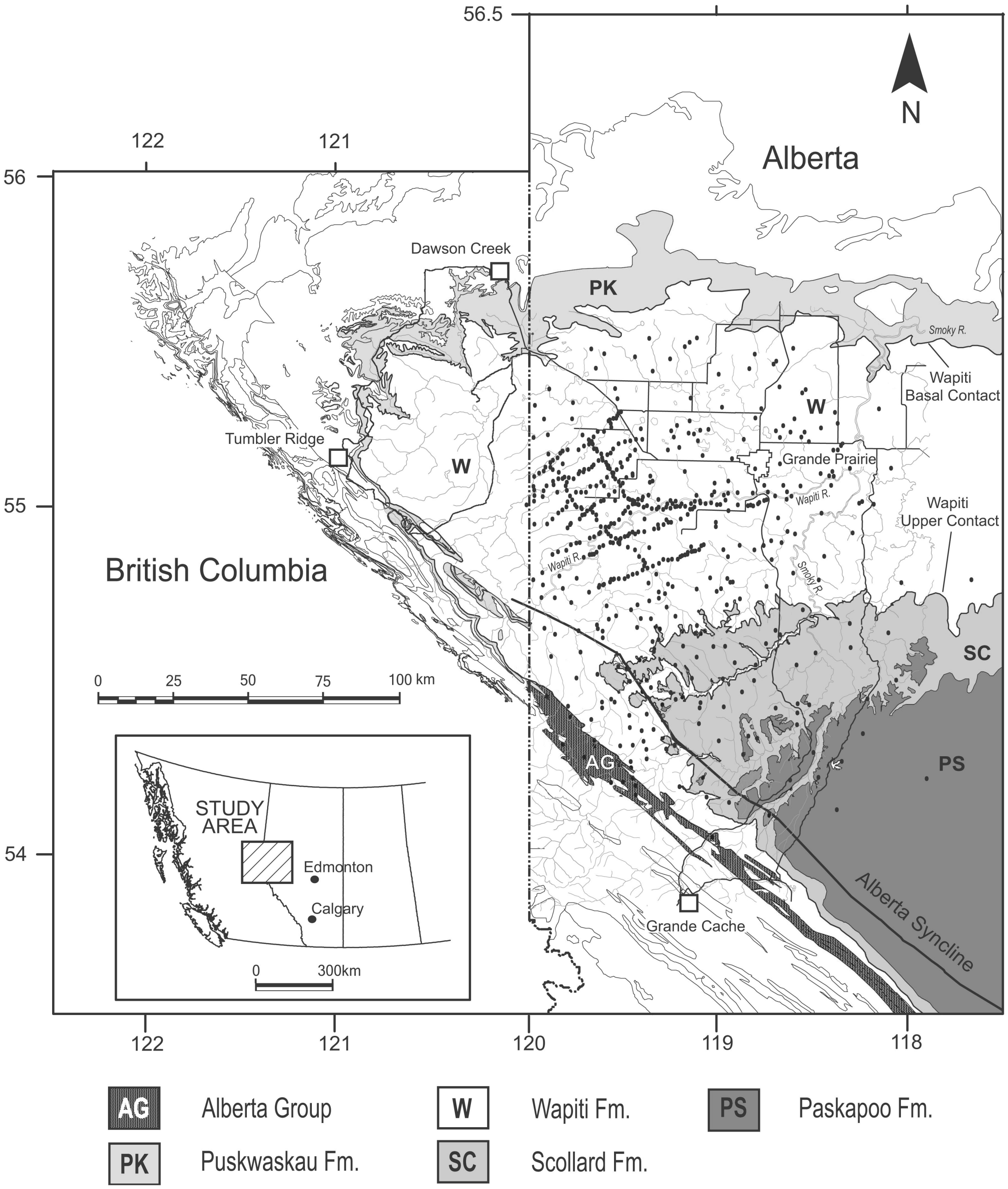
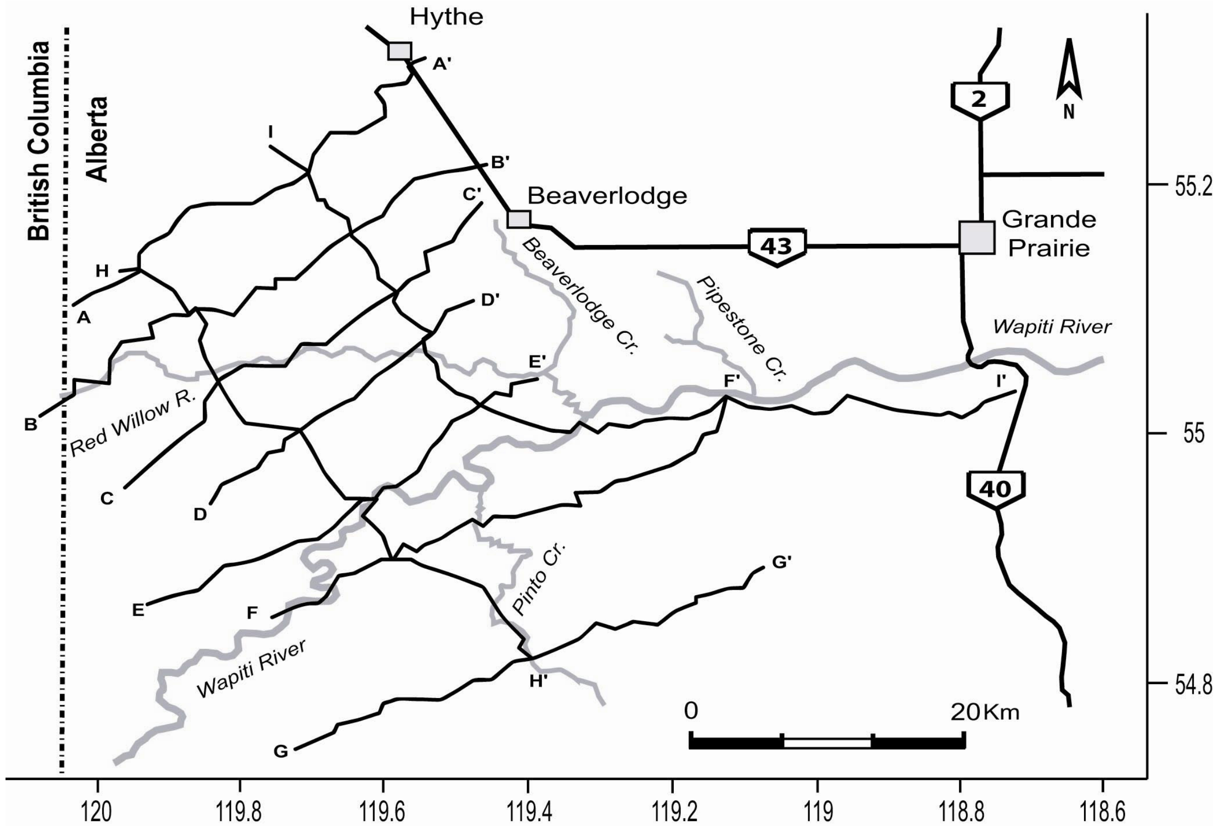
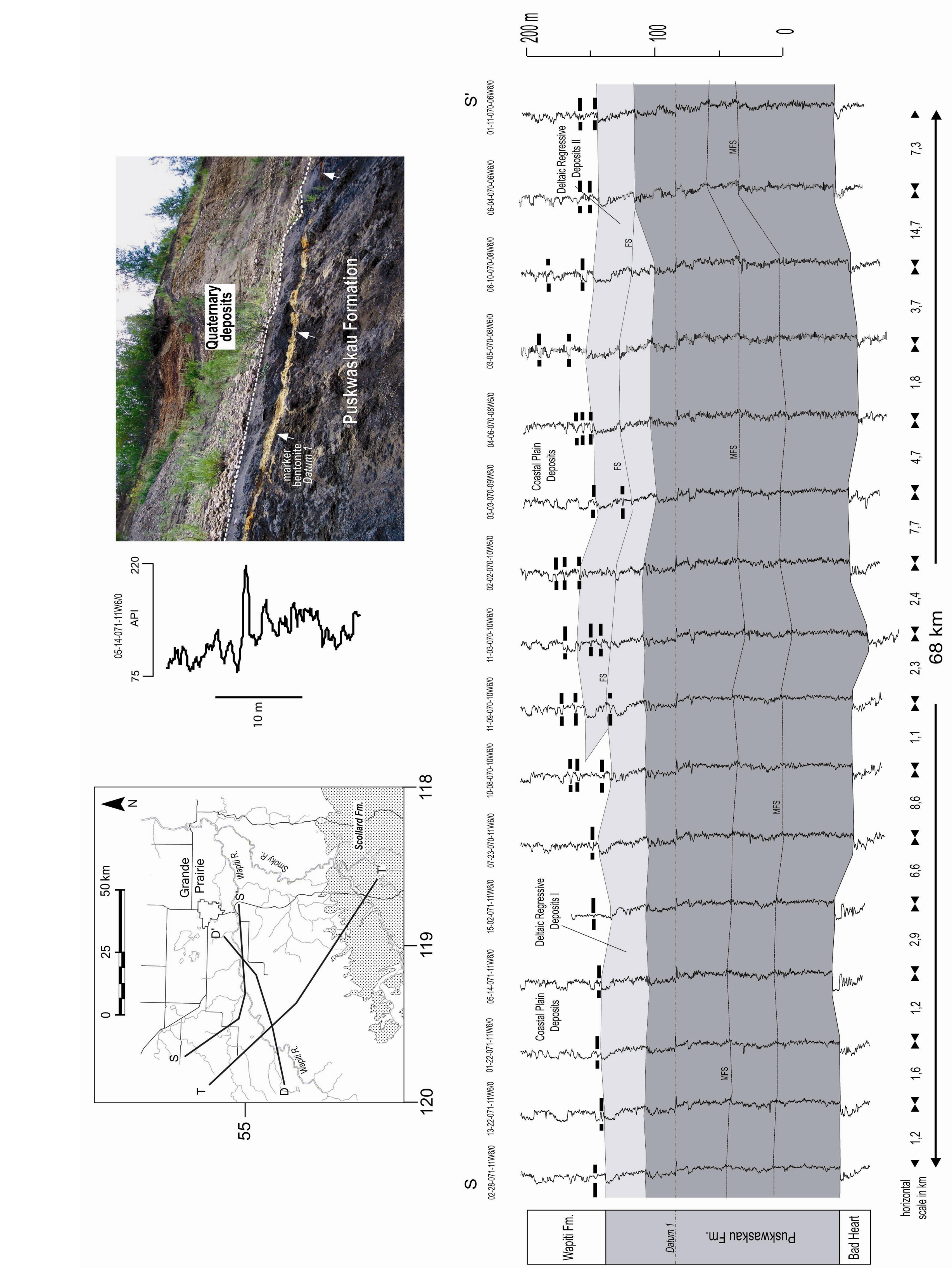

56.5
N
Alberta
122
121
56
Dawson Creek
PK
Smoky R.
Wapiti
Basal Contact
W
Tumbler Ridge
Grande Prairie
W
55
Wapiti R.
Wapiti
Upper Contact
British Columbia
Wapiti R.
Smoky R.
SC
0
25
50
75
100 km
AG
PS
STUDY
AREA
54
Edmonton
Calgary
Grande Cache
Alberta Syncline
0
300km
122
121
120
119
118
AG
Alberta Group
W
Wapiti Fm.
PS
Paskapoo Fm.
PK
Puskwaskau Fm.
SC
Scollard Fm.

Figure 2



	Wells N°	Lenght (km)	Average well distance (m)	Orientation
Section A-A'	27	38	1662	SW-NE
Section B-B'	29	45	1763	SW-NE
Section C-C'	22	39	2077	SW-NE
Section D-D'	19	29	1673	SW-NE
Section E-E'	24	39	1769	SW-NE
Section F-F'	33	46	1557	SW-NE
Section G-G'	32	43	1442	SW-NE
Section H-H'	33	52	1724	NW-SE
Section I-I'	60	78	1385	NW-SE/E-W
Total Wells	266			
Total lenght (km)		409		

Figure 3



Grande Prairie
50 km
0
25
55
120
119
118
Wapiti R.
Smoky R.
Scollard Fm.
S
S'
T
T'
D
D'
05-14-071-11W6/0
API
75
220
10 m
Quaternary deposits
marker bentonite
Datum 1
Puskwaskau Formation
Coastal Plain Deposits
Deltaic Regressive Deposits I
Deltaic Regressive Deposits II
FS
MFS
200 m
100
0
68 km
horizontal scale in km
Wapiti Fm.
Puskwaskau Fm.
Bad Heart

Figure 4

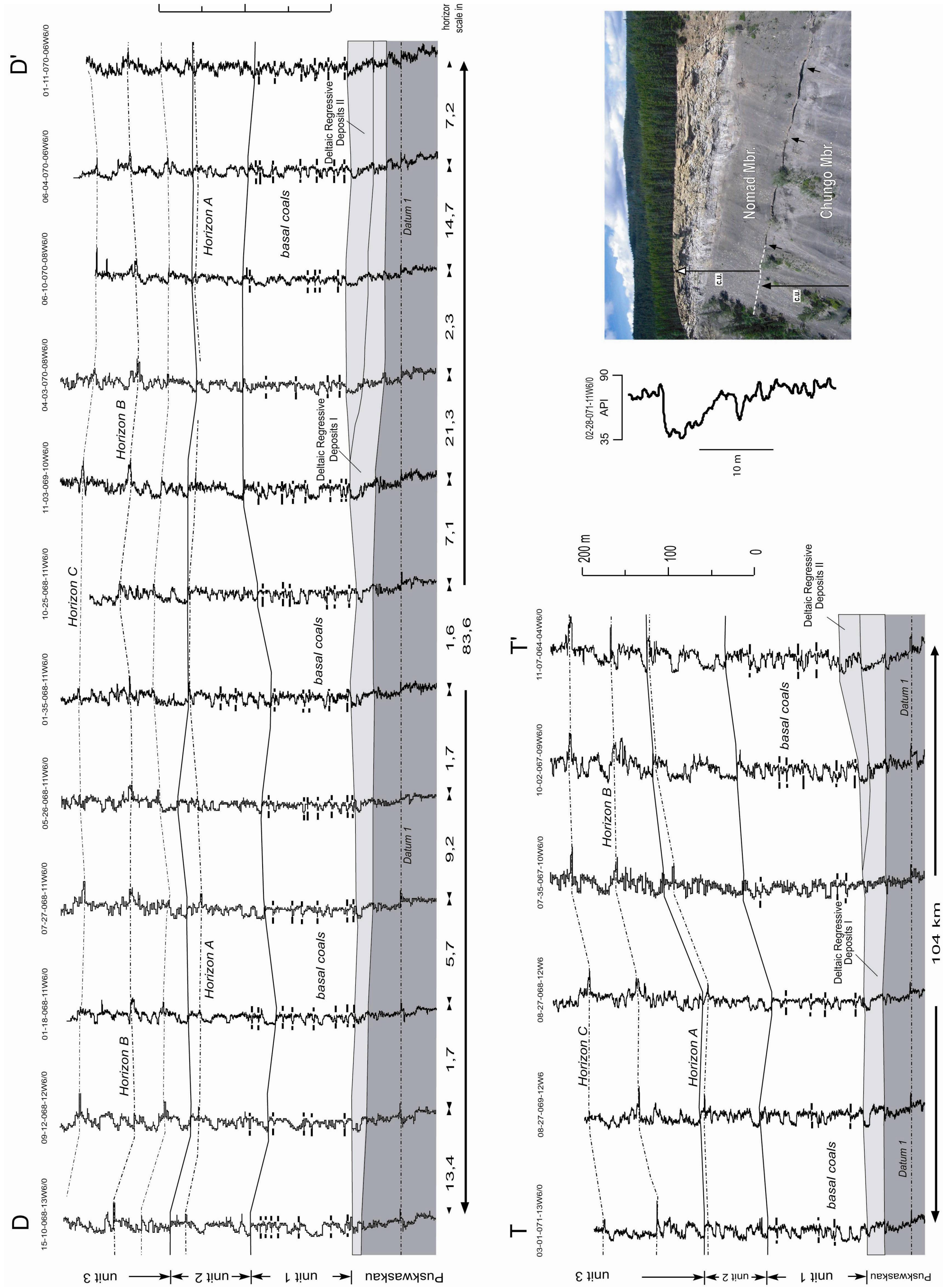

D
D'
T
T'
15-10-068-13W6/0
09-12-068-12W6/0
01-18-068-11W6/0
07-27-068-11W6/0
05-26-068-11W6/0
01-35-068-11W6/0
10-25-068-11W6/0
11-03-069-10W6/0
04-03-070-08W6/0
06-10-070-08W6/0
06-04-070-06W6/0
01-11-070-06W6/0
Horizon A
Horizon B
Horizon C
basal coals
Deltaic Regressive Deposits I
Deltaic Regressive Deposits II
Datum 1
unit 3
unit 2
unit 1
Puskwaskau
13,4
1,7
5,7
9,2
1,7
1,6
83,6
7,1
21,3
2,3
14,7
7,2
03-01-071-13W6/0
08-27-069-12W6
08-27-068-12W6
07-35-067-10W6/0
10-02-067-09W6/0
11-07-064-04W6/0
104 km
200 m
100
0
02-28-071-11W6/0
API
35
90
10 m
Nomad Mbr.
Chungo Mbr.
c.u.

Figure 5

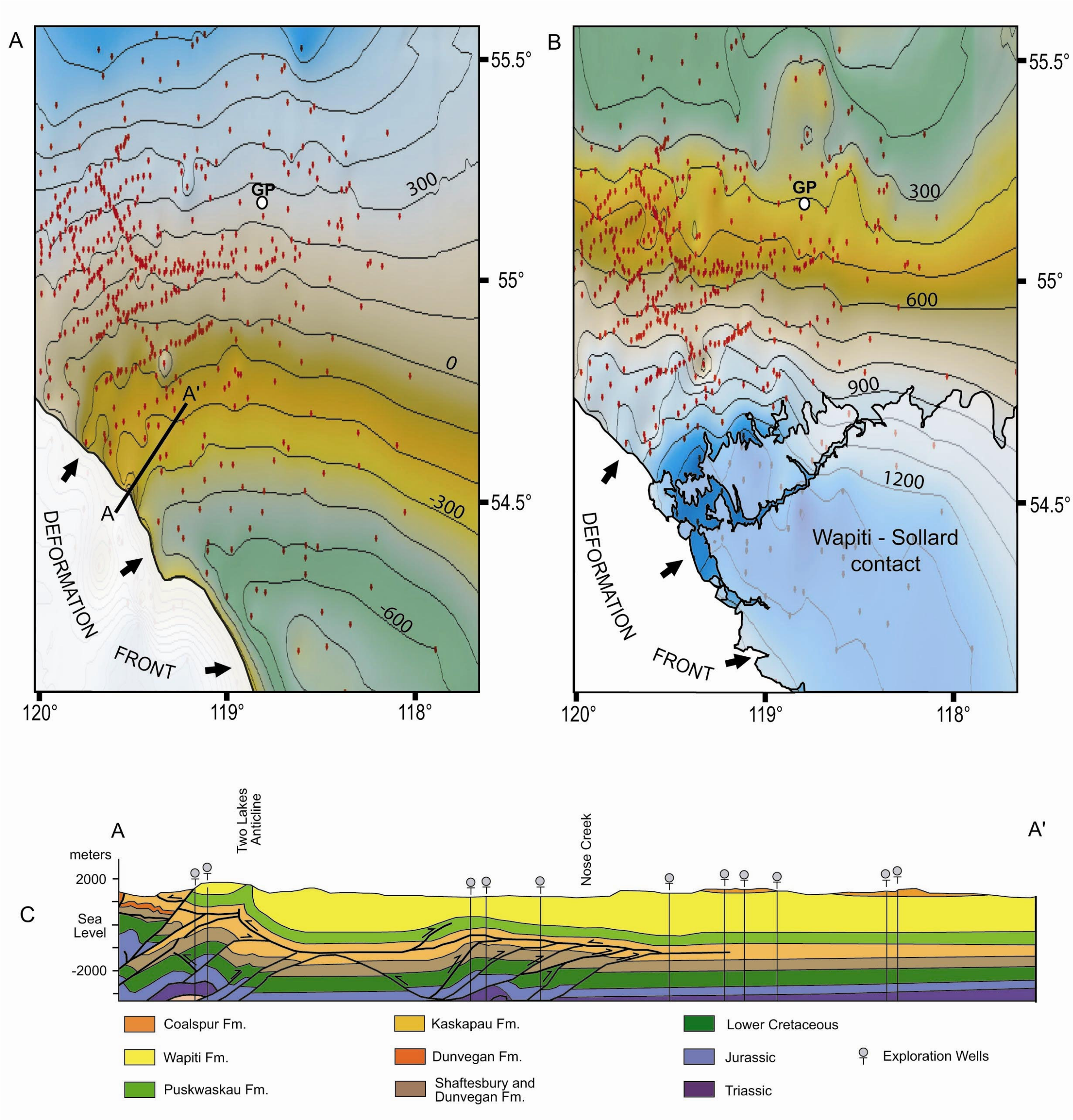
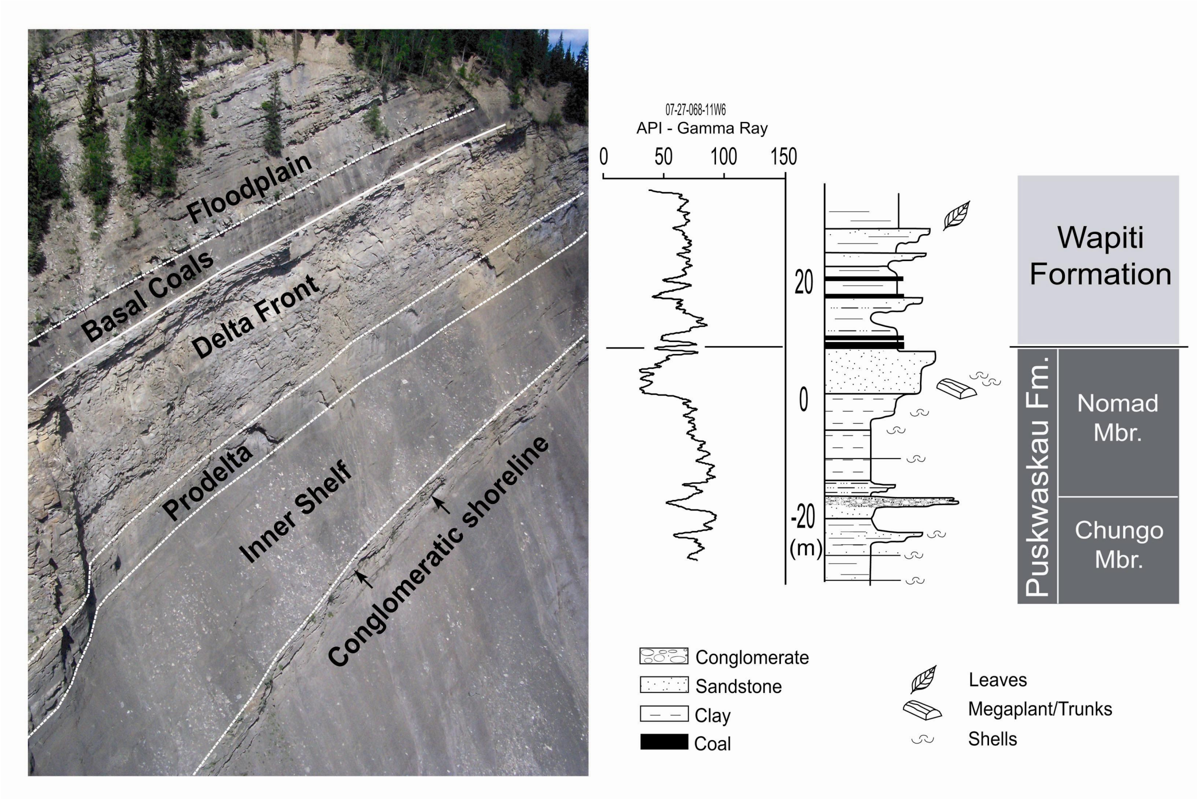

A
B
C
55.5°
55°
54.5°
120°
119°
118°
GP
300
0
-300
-600
600
900
1200
A
A'
DEFORMATION
FRONT
Wapiti - Sollard contact
Two Lakes Anticline
Nose Creek
meters
2000
Sea Level
-2000
Coalspur Fm.
Wapiti Fm.
Puskwaskau Fm.
Kaskapau Fm.
Dunvegan Fm.
Shaftesbury and Dunvegan Fm.
Lower Cretaceous
Jurassic
Triassic
Exploration Wells

Figure 6



Floodplain
Basal Coals
Delta Front
Prodelta
Inner Shelf
Conglomeratic shoreline
07-27-068-11W6
API - Gamma Ray
0
50
100
150
20
0
-20
(m)
Wapiti Formation
Puskwaskau Fm.
Nomad Mbr.
Chungo Mbr.
Conglomerate
Sandstone
Clay
Coal
Leaves
Megaplant/Trunks
Shells

Figure 7

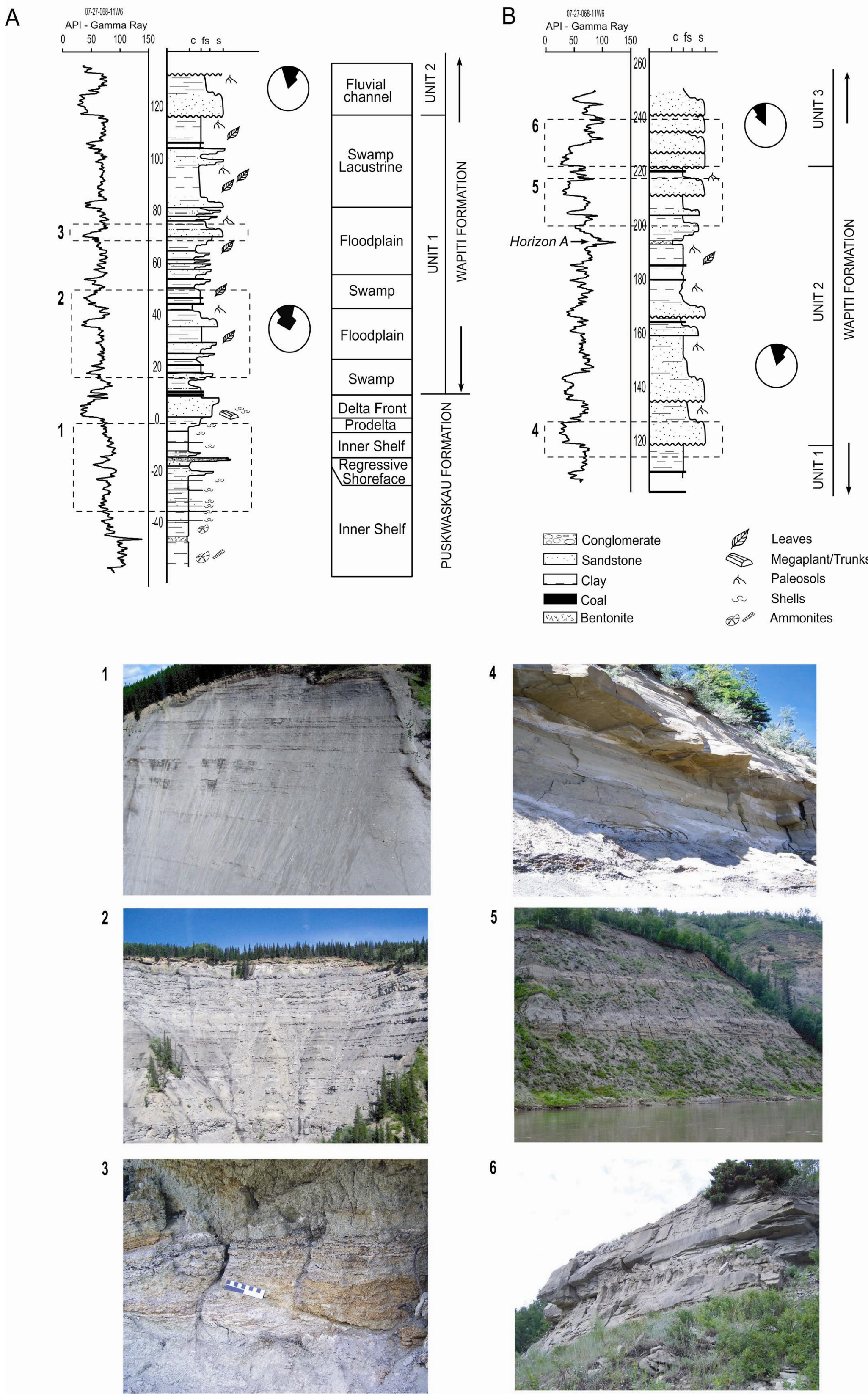

A
07-27-068-11W6
API - Gamma Ray
c fs s
Fluvial channel
Swamp Lacustrine
Floodplain
Swamp
Floodplain
Swamp
Delta Front
Prodelta
Inner Shelf
Regressive Shoreface
Inner Shelf
UNIT 2
UNIT 1
WAPITI FORMATION
PUSKWASKAU FORMATION
B
07-27-068-11W6
API - Gamma Ray
Horizon A
UNIT 3
UNIT 2
UNIT 1
WAPITI FORMATION
Conglomerate
Sandstone
Clay
Coal
Bentonite
Leaves
Megaplant/Trunks
Paleosols
Shells
Ammonites

Figure 8

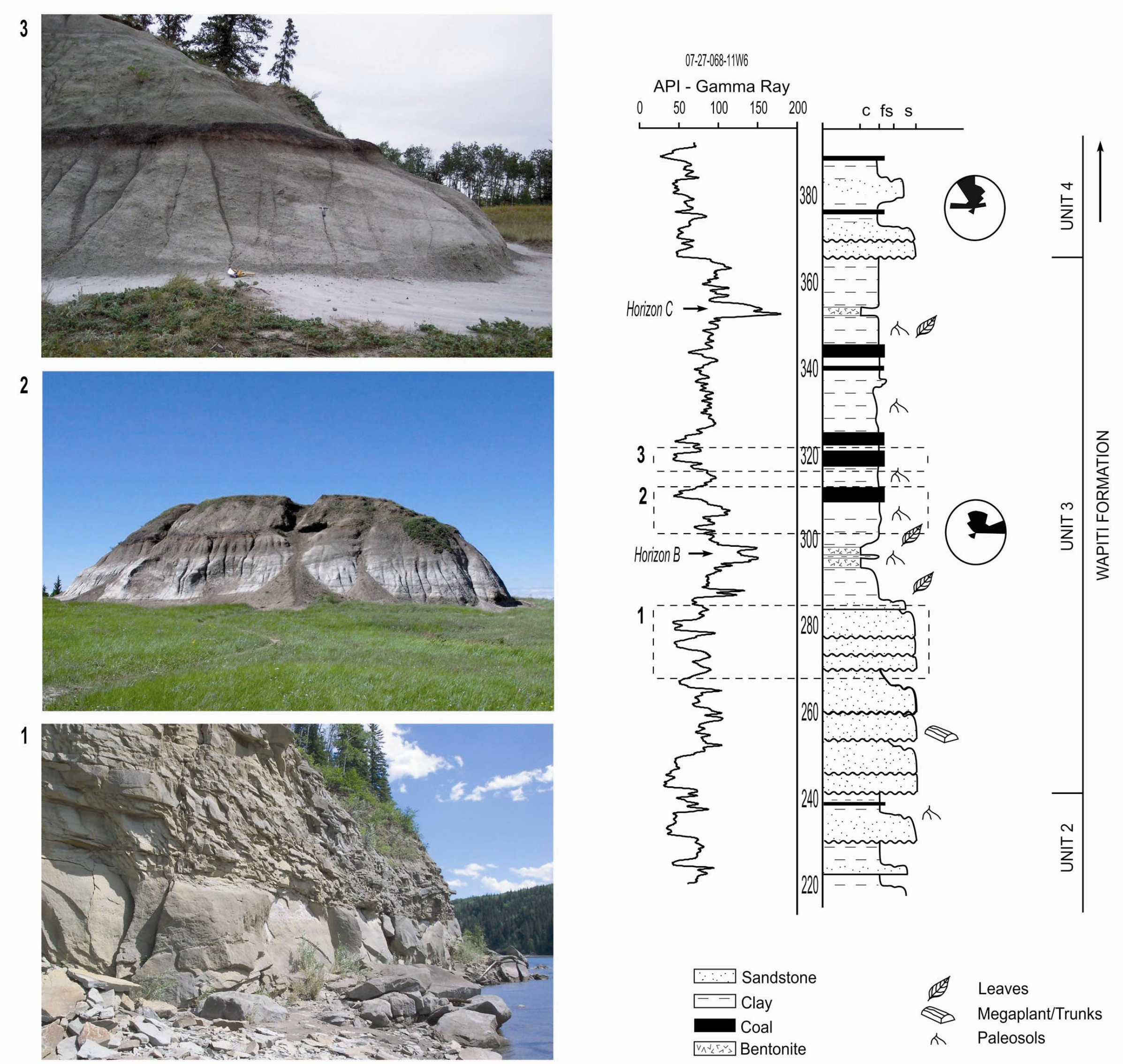

3
2
1
07-27-068-11W6
API - Gamma Ray
0 50 100 150 200
c fs s
380
360
340
320
300
280
260
240
220
Horizon C
Horizon B
UNIT 4
UNIT 3
UNIT 2
WAPITI FORMATION
Sandstone
Clay
Coal
Bentonite
Leaves
Megaplant/Trunks
Paleosols

Figure 9

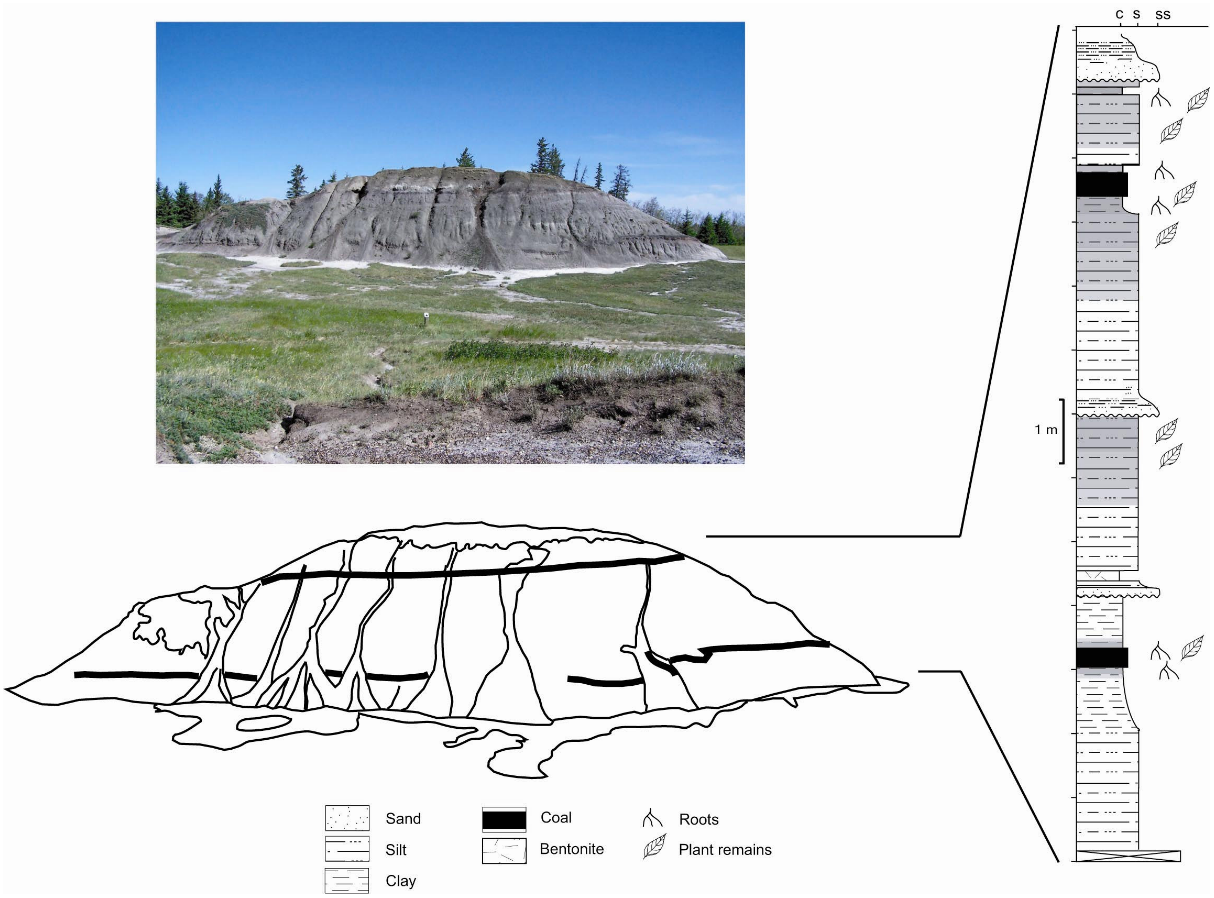


Figure 10

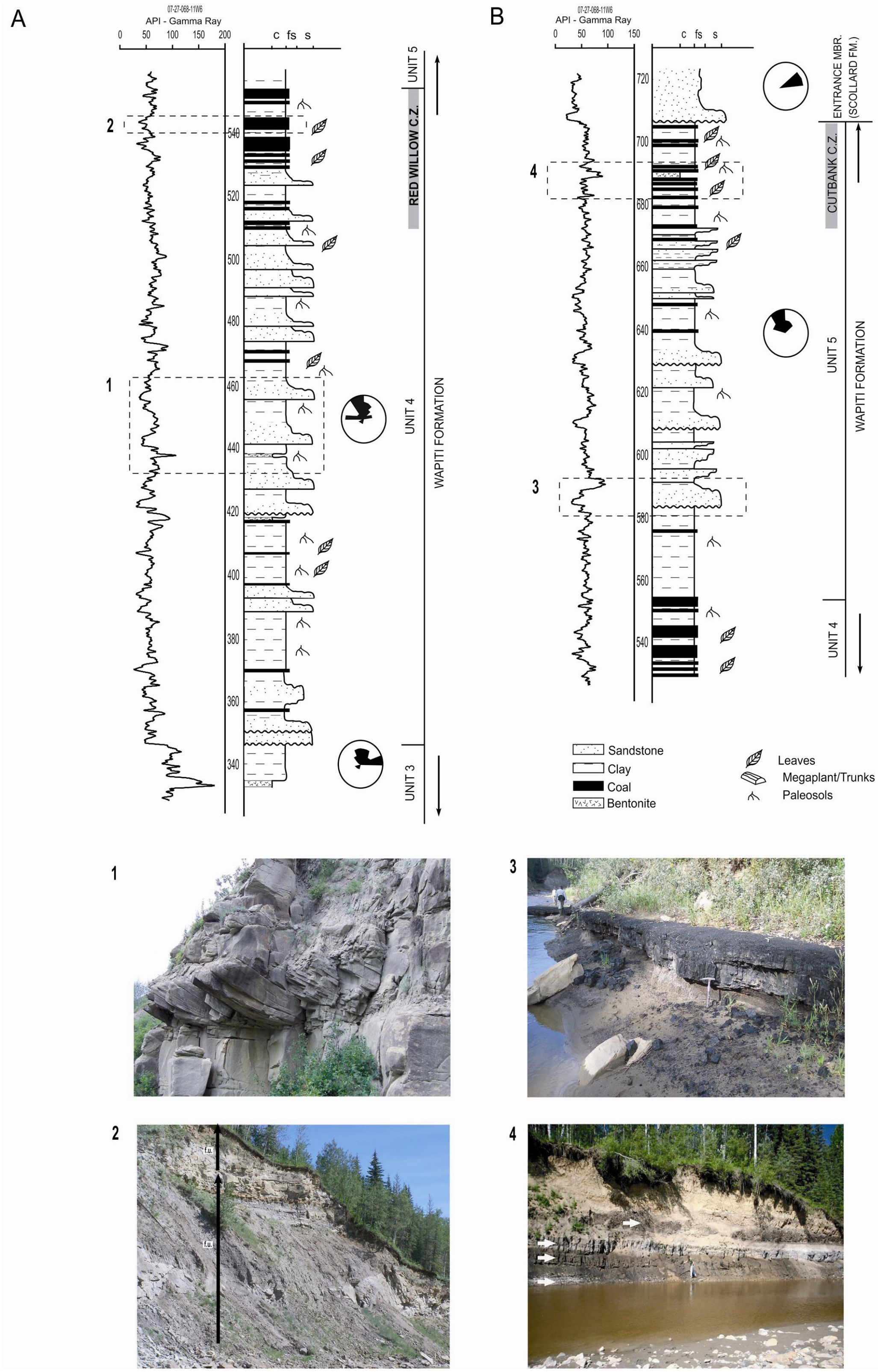

A
07-27-068-11W6
API - Gamma Ray
0 50 100 150 200
c fs s
UNIT 5
RED WILLOW C.Z.
UNIT 4
WAPITI FORMATION
UNIT 3
B
07-27-068-11W6
API - Gamma Ray
0 50 100 150
ENTRANCE MBR. (SCOLLARD FM.)
CUTBANK C.Z.
UNIT 5
WAPITI FORMATION
UNIT 4
Sandstone
Clay
Coal
Bentonite
Leaves
Megaplant/Trunks
Paleosols
1
2
3
4

Figure 11

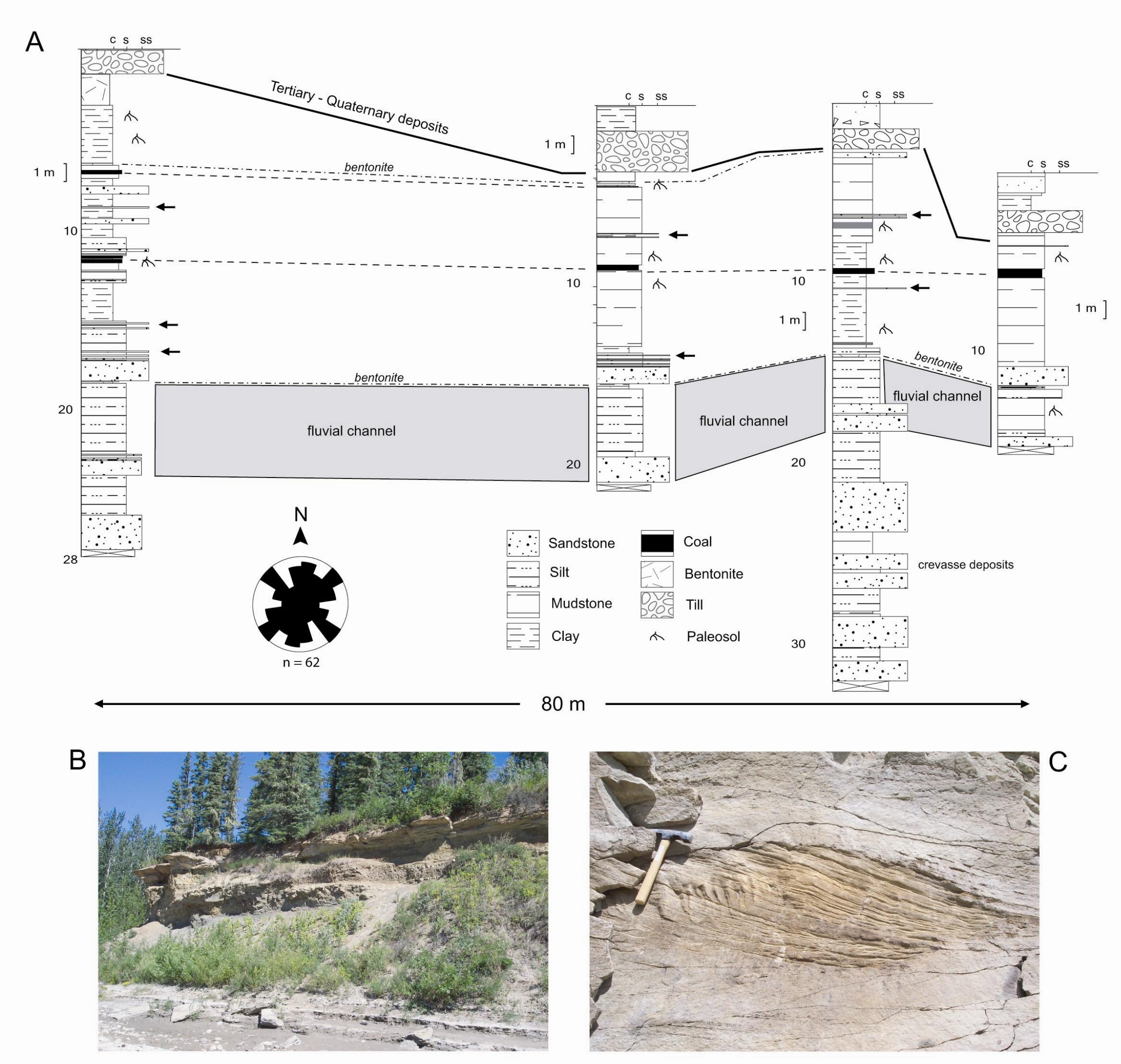

A
B
C
c s ss
Tertiary - Quaternary deposits
bentonite
1 m
10
20
28
fluvial channel
crevasse deposits
30
N
n = 62
Sandstone
Silt
Mudstone
Clay
Coal
Bentonite
Till
Paleosol
80 m

Figure 12

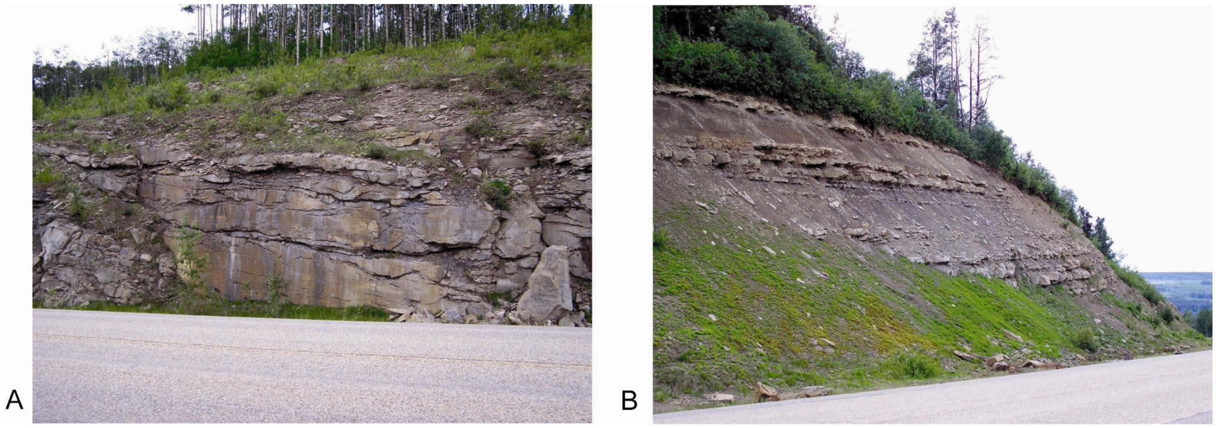


Figure 13

Paper 2

Bentonite chemical features as proxy of Late Cretaceous provenance changes: a case study from the Western Interior Basin of Canada.

Federico Fanti

Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Università di Bologna, Via Zamboni 67, 40126 Bologna, Italy

Corresponding author: Tel: +39 051 2094565; Fax: +39 051 2094522;

Email: federico.fanti@unibo.it

Abstract

Bentonite beds are fairly common in both marine and terrestrial Upper Cretaceous (Campanian-Maastrichtian) deposits of the Western Interior Basin of western Canada and north-western United States. A detailed stratigraphic, sedimentologic, geochemical (X-ray fluorescence), and mineralogical (X-ray diffraction) study of twenty-one bentonites from the Puskwaskau and Wapiti formations in the Grande Prairie area (west-central Alberta, Canada) is here presented. Major and trace element concentrations from altered volcanic ashes document the presence in the study area of predominantly trachy-andesitic and rhyolitic volcanogenic products, resulted from intense volcanic arc to within-plate pyroclastic activity. Concentration values of high field strength elements (HFSE) and selected large ion lithophile elements (LILE) (e.g. Nb, Zr, Th, and Y) obtained by X-ray fluorescence spectroscopy strongly support the presence of multiple volcanic sources. Integrated paleoenvironmental and geochemical criteria for provenance determination indicate a bimodal occurrence of basic and acid volcanic products interpreted as reflection of source areas characterized by different tectonic setting and magmatic composition. A comparative analysis of geochemical compositions between Grande Prairie bentonites and 30 known volcanic beds from central and southern Alberta, Manitoba and Montana 1. documents a trend toward more acidic and alkali-depleted volcanic products during the late Campanian-early Maastrichtian interval, and 2. suggests a well constrained stratigraphic and geographic subdivision of the non-marine successions of the foreland basin on the basis of geochemical characteristic of volcanic ash beds. Furthermore, geochemical "fingerprints" of several decimeter to meter thick bentonite beds have been coupled with volcanic ash subsurface signature in order to investigate their role as marker beds. This multiple-approach provides a reliable tool for basin-scale identification and correlation of non-marine sedimentary successions.

Keywords: Sediment provenance; Geochemistry; Bentonite; Late Cretaceous; Wapiti Formation; Puskwaskau Formation.

1. Introduction

Discrimination of sediment geochemistry has been used successfully to determine tectonic setting and provenance of different deposits in the study of complex geological areas. In particular, geochemical techniques applied to sandstone and volcanites analyses represent an essential tool in interpreting the geological evolution of ancient clastic-dominated sedimentary basins (Rahmani and Lerbekmo, 1975; Taylor and McLennan, 1985; McLennan et al., 1990, 1993; Pearce and Jarvis, 1992; Fralick and Kronberg, 1997; Pearce et al., 1999; Dinelli et al., 1999; Zhengjun et al., 2005; Curzi et al., 2006). Geochemical analyses have been largely employed to discuss sediment provenance, depositional environmental and chemical conditions, as well as correlations between thick stratigraphic successions over large geographic areas (Mack and Jerzykiewicz, 1988; Pellenard et al., 2003; Armstrong-Altrin et al., 2004**;** Schnurr et al., 2007). A growing number of papers has dealt with the geochemical and mineralogical characterization of altered volcanic ash deposits documenting how detailed analysis of such parameters may provide a powerful tool to perform stratigraphic correlations and discern changes in provenance of volcanogenic deposits in both marine and terrestrial successions (Lerbekmo, 1968; Thomas et al., 1990; Baadsgaard et al., 1993; Cadrin et al., 1995; Bertog, 1999; Bertog and Huff, 1999; Christidis, 2001; Desmares et al., 2002, 2007; Lerbekmo, 2002; Schnurr et al., 2007; Foreman et al., 2008). The present paper reports a case study evidencing how the integration of different data sets (geochemistry, mineralogy, lithology, and subsurface signature) from bentonite beds allows 1. a reliable chronostratigraphic and geographic subdivision of adjacent successions within a foreland basin, and 2. a powerful tool for the identification of sediments area source in both marine and non-marine strata.

Late Campanian to Early Paleocene sediments of the Western Interior Basin of Canada and northern U.S. were derived primarily from three types of rocks: volcanic (generally andesites and dacites), low-grade metamorphic, and sedimentary rocks (Mack and Jerzykiewicz, 1988; Eberth and Hamblin 1993). This foreland basin is also characterized by fairly common altered volcanic ash beds in both marine and terrestrial Late Cretaceous successions. Bentonite beds have been largely used also as chronostratigraphic markers in the Western Interior Basin deposits mainly as a source for radioisotopic ages, most of which from $^{40}Ar/^{39}Ar$ ratios (Obradovich and Cobban, 1975; Williams and Baadsgaard, 1975; Goodwin and Deino, 1989; Eberth and Deino, 1992; Obradovich, 1993; Rogers et al., 1993; Hicks et al., 1995; Hicks et al., 1999; Roberts and Hendrix, 2000; Payenberg et al., 2002; Roberts et al., 2005; Lehman et al., 2006). This study reports a detailed analysis on the compositions of twenty-one altered volcanic ash beds from the Upper Cretaceous (Campanian-Maastrichtian) marine Puskwaskau Formation and non-marine Wapiti Formation in the Grande Prairie area (northwestern Alberta, Canada). Major and trace element concentrations and diagenetic history were determined for all samples combining X-ray fluorescence and X-ray diffraction spectroscopy. Detailed outcrop stratigraphic and sedimentologic analyses were integrated with subsurface data and geochemical “fingerprints” in order to evaluate whether sufficient parameters exists for bentonites to be individually identifiable and mappable on a regional scale. Discrimination diagrams were used to estimate the original magma composition and tectonic setting, and therefore compare such compositions with age equivalent bentonites from western Canada (Alberta and Manitoba) and northern U.S. (Montana).

2. Location and geological background

The project area encompasses approximately 15.000 km^2 in the Grande Prairie district in northwestern Alberta (Fig. 1) extending from the Cutbank River in the south (Twp. 63) to the Puskwaskau Creek in the north (Twp. 76). The region is incised by major rivers such as the Wapiti and the Smoky, and several smaller drainage systems that include the Kleskun, Mountain and Pinto creeks; major outcrops are restricted to river bank exposures and roadcuts. In this area, dark grey marine shales of the Puskwaskau Formation (Smoky Group, Stott, 1961; Hu, 1997; Dawson et al., 1994a) are overlaid by nonmarine deposits of the Wapiti Formation which consists of interbedded fluvial sandstone and siltstone with minor mudstone and coal, and subordinate lacustrine deposits. This sedimentary succession is equivalent to the uppermost Lea Park Formation, Belly River Group (Foremost, Oldman and Dinosaur Park formations), Bearpaw Formation, and Edmonton Group (Horseshoe Canyon, Whitemud, and Battle formations) of central and southern Alberta (Eberth, 1990, 2002, 2005; Eberth and Hamblin, 1993; Dawson et al., 1994a, b; Jerzykiewicz and Norris, 1994; Eberth and Brinkman, 1997; Brinkman, 2003, Fanti, 2007), all known for their abundance of fossil vertebrates. In despite these important premises, to date the Wapiti succession has been poorly studied with the exception of few reports on the coal potential and overall geological description of the formation (Allan and Carr, 1946; Byrne, 1955; Stott, 1961; Dawson et al., 1994a, b; Fanti, 2007 and references therein).

3. Material and methods

Field studies and sampling in the Grande Prairie region consisted of three summer campaigns undertaken in 2006, 2007, and 2008. River boat prospecting coupled with surface mapping and trenching were carried out in order to sample approximately 30 kg of each volcanic ash layer as required for all laboratory procedures, including zircon separation for radiometric ages (Fanti et al., in prep.). Modification in clay mineralogical compositions and other measured parameters related to weathering processes depends on a number of variables, including lithology, permeability, climate, and intensity and duration of weathering. In order to minimize weathering effects on geochemical and mineralogical analyses, outcrops were excavated and sampled to a depth of 40 cm. GPS data were collected using the WGS 84 Datum and plotted into regional maps accordingly. Sampling locations in the study area are shown in Fig. 1.

The term "bentonite" has been used in the literature with a certain degree of uncertainty depending on the weight given to its origin rather than composition: since bentonite clay mineralogy primarily results from diagenetic alteration of volcanic products, the terms *bentonite* and *altered volcanic ash* have been used interchangeably (Byrne, 1955; Grim and Guven, 1978; Roen and Hosterman, 1982, Thomas et al., 1990). Therefore, these terms hereafter indicate a soft, light colored, plastic rock composed essentially of clay minerals of the montmorillonite group and produced by devetrification of a glassy igneous material, commonly a tuff or volcanic ash (Bates and Jackson, 1987). In ascending stratigraphic order, samples discussed in this study and respective abbreviations are as follow: Puskwaskau (PSK), White Mountain (WM), Bear Creek (BC), Horizon B 1 (HB1), Horizon B 2 (HB2), Kleskun Hill Bentonite (KHB), Lizard Hill (LH), Kleskun Hill Top (KHT), Wapiti River Bridge (WRB), Spring Creek (SC), Wapiti-Pipestone 1 (WP1), Wapiti-Pipestone 2 (WP2), Pipestone Creek (PC), Wapiti River (WR), Red Willow 2007 (RW07), Red Willow 3 (RW3), George Robinson (GR), Wapiti Bonebed (WB), Pinto Creek 2006 (P06), Pinto Creek 2007 (P07), and Cutbank River (CR). Detailed information on location, stratigraphic position, thickness and field characteristics of discussed horizons are presented in Table 1 and Fig. 2.

Exposures were referred to composite stratigraphic columns in order to determine relative positions. High resolution subsurface geophysical data (gamma ray curves from well logs) allowed a detailed documentation of the geometry and lateral variation of the bentonitic beds. Discrimination diagrams of Winchester and Floyd (1977) and Le Bas et al. (1986) were used to investigate original magma type of the bentonites: the latter reference is reported below as TAS (total alkali-silica). Incompatible trace-element plots after Pearce et al. (1984) were combined to assign the tectonic setting of the volcanic source rocks.

3.1 XRF methods

Chemical compositions (major, minor, and trace elements) were obtained by X-ray fluorescence spectrometry (XRF) (Philips PW 1480) on pressed powder pellets, following the matrix correction methods of Franzini et al. (1972, 1975), Leoni and Saitta (1976) and Leoni et al. (1982). The estimated precision and accuracy, compared with the analysis of international reference materials, are better than 5% for trace-elements determinations, except for those at concentrations of <10 ppm

(10-15%). Detection limits are 3 ppm according to the analytical conditions. LOI (Loss on Ignition) was determined after overnight heating at 950°C.

3.2 XRD methods

Mineralogical analyses of bentonite samples were performed by powder X-Ray Diffraction (XRD) using a Philips PW 1710 diffractometer, Cuα radiation (λ Alpha 1, 1.54056; λ Alpha 2, 1.54439; Ratio Aplha 2/1, 0.5), 40kV/30 mA, data angle range from 3.015 to 59.985, continuous scan, step size 0.03, step time 1.45.

4. Bentonite beds: field and macroscopic characteristics

Bentonite beds from the study region were firstly reported by Rutherford (1930) in the badland-like outcrops of the Kleskun Hill area, north east of Grande Prairie: these beds and few others along the Wapiti River were later briefly investigated for geotechnical and industrial purposes (Byrne, 1955; Carter, 1957; Geo-Engineering Ltd, 2005). In addition, KHB and PC have been processed for $^{40}Ar/^{39}Ar$ isotopic dating, providing an age of 73.77 ± 1.46 and 73.25 ± 0.25 Ma respectively (David Eberth, pers. comm. 2005). Bentonites discussed in this study vary significantly both in color (from dark grey to olive to yellow) and layer thickness (from 10 to 350 cm, Table 1). Volcanic beds have sharp basal and upper contacts, and generally exhibit high lateral variation in thickness. Being deposited as volcanic ash falls, bentonite beds are found in a variety of depositional environments, ranging from shallow marine shale to alluvial plain facies association (Fig. 2). The vast majority of the bentonites, however, occur in association with fine grained, organic-rich overbank mudstones and clays, wet and immature paleosols, and lacustrine/palustral deposits. In addition, altered ash beds are sporadically found amalgamated with basal channel sandtones: such bentonites contain a resistant and pervasive carbonatic cement. These deposits are fairly common at the merge of the Red Willow and Wapiti Rivers, and at the Kleskun Hill. Lastly, no vertical grain size changes in the ash beds were documented at sampling localities (Fig. 3). Bentonite stratigraphic occurrence also suggests an increase in volcanic activity from the middle Campanian onward, with a peak concomitant with the Bearpaw transgressive event. In fact, eleven of the 21 bentonites described below occur in the ~74-73 Ma interval, whereas only eight volcanic beds are documented in the broader 73-67 Ma interval.

5. Geochemistry

The geochemical and mineralogical features of samples has been investigated to 1) document the composition of volcanic ashes, 2) identify the nature of parent volcanism and relative tectonic setting, and 3) test the potential of bentonite geochemistry as a discriminating factor for the identification of time and/or space variations along the eastern margin of the Canadian cordillera during the late Cretaceous. The geochemical database comprises XRF analyses of Grande Prairie samples for major oxides and trace elements combined with those reported in the literature for age equivalent bentonites from Alberta, Montana and Manitoba. For all geochemical diagrams presented below, major element concentrations were recalculated to 100% on a water free basis. LOI values range between 23,33% and 4,85%: however, if the anomalously high value of bentonite PSK is discarded , the range is reduced to 16,8%. Whole-rock geochemical compositions of altered volcanic ash layers from the Grande Prairie area are reported in Table 2.

5.1 Major elements

XRF analyses indicate that several major oxides have a broad range of concentration. For example, SiO_2 Wt% ranges from 47.2 to 72.34; Al_2O_3 from 13.43 to 25.63; MgO from 0.82 to 4.35; alkali (K_2O+Na_2O) from 0.6 to 5.78. High alumina-to-silica ratio (range 2.01-5.38, av. 3.3) and relatively low alkali contents indicate consistent alteration from ash to bentonite, as also documented by XRD analyses. Loss of alkalis and high values of MgO in cinerite compositions are in fact strongly influenced by the progressive transformation in montmorillonite and other clay minerals, characterized by essential Mg requirement. This process resulted from intensive weathering, burial diagenesis, percolating groundwater, and possibly localized hydrothermal activity. AFM (Irvine and Baragar, 1971) and SiO_2-K_2O (Peccerillo and Taylor, 1976) plots indicate that sixteen samples fall in the calc-alkaline series field, whereas five are tholeiitic (Fig. 4). Whole-rock variations of SiO_2 vs K_2O/Na_2O ratio indicate that the bentonites described in this study have predominantly andesitic and dacitic compositions with relatively low alkali contents.

Multi-element plots of major chemical elements indicate that Al_2O_3 and MgO have the lowest degree of variability within samples, whereas the widest variations are those of Na_2O (0.3-2.7 wt%), K_2O (0.3-3.08 wt%), and Fe_2O_3 (2.6-7.66 wt%). In addition, following Land et al. (1997) and Christidis (1998), the intercept of a regression line on the ordinate will be positive if an element is lost and negative if it has been gained relative to a mobile component. Hence Ti, Na and K have been enriched relative to SiO_2, whereas Mg, Ca, P, and Fe have been depleted (Fig. 5A).

5.2 Trace elements

Previous studies on altered volcanic deposits indicate that incompatible elements such as Ce, Ga, Nb, Y, and Zr, tend to remain stable under diagenetic conditions (Thomas et al., 1990; Christidis, 1998; 2001; Pellenard et al., 2003; Foreman et al., 2008). Trace element mobility plots on Grande Prairie bentonites show that Ba, Cr, and Rb are significantly mobile and thus unsuitable for chemical characterization (Fig. 5B). On the contrary, the high field strength elements (HFSE) such as Nb and Zr and selected large ion lithophile elements (LILE) (e.g. Th, Y) are considered to be resistant to alteration processes: in fact, they show little variation in the alteration profile and therefore can provide useful petrological information unrelated to late modification processes. Considering Zr as immobile element Ba, Ce, La, Rb, Sr, and Y have been enriched, whereas Cr and Ni have been depleted (Fig. 5B). To better define the possible relationship between age and geochemical features, Th, Y, Nb, Zr, La, Ce, TiO_2, SiO_2 and Th/K_2O and Zr/Nb ratios were plotted on a stratigraphic basis (Fig. 6). Even considering the presence of a significant gap in the data for the lowermost deposits of the Wapiti Formation (i.e. units 1 and 2), with the sole WM bentonite identified, the plots clearly indicates that no specific time related trend characterizes the analyzed samples. Stratigraphic distribution of the bentonite beds, however, indicate the presence of two distinct peaks of explosive activity recorded in the sedimentary succession within discrete stratigraphic intervals representative of relatively short time intervals (approximately 1 Ma). Such intervals are also characterized by major oscillations of all considered elements, oxides, and element ratios.

The first interval, stratigraphically confined within the lower unit 3 of the Wapiti Formation (Fanti, 2007; Fanti and Catuneanu, in prep.), includes the BC, HB1, and HB2 ash beds. In spite of major differences in concentration of elements such as Th, Y, and Nb, these samples have similar Zr/Nb ratios (7.70, 3.9, and 3.58 respectively), and therefore may represent different degrees of fractional crystallization of a single source. Zr and Nb, in fact, are generally considered to behave similarly in petrogenetic processes such as fractional crystallizations: therefore their similar ratios in different volcanics may indicate a common source. Nb/Y ratio (Pearce et al., 1984) suggests different tectonic conditions for original magma between HB1 and BC (VAG and syn-COLG), and HB2 (WPG) (Fig. 7). However, such differences with all probability reflect derivation from a more differentiated magma rather than a different tectonic setting.

Eight bentonitic beds (KHB, LH, KHT, WRB, SC, WP1, WP2, and PC) are representative of the second stratigraphic interval characterized by a significant increase of explosive volcanic event preserved in the sedimentary record. Interestingly, such deposits are roughly equivalent in age to the Bearpaw transgressive event in central and southern Alberta. Remarkable differences in concentrations of single elements and oxides (particularly Y, Zr, Ce, TiO_2, and SiO_2) are also observed in the Zr/Nb ratio. With respect to this ratio, limit values for this interval are represented by sample WRB (≤ 2) and KHT (≥ 15). This difference in values suggests the presence of two distinct volcanic sources, of which samples KHB, LH, SC, WP1, WP2, and PC possibly represent mixed products. To support this hypothesis, the Nb/Y discrimination diagram after Pearce et al. (1984) indicates diverse tectonic setting for parental volcanic rocks of KHB and WRB, classified respectively as within-plate and volcanic arc/syn-collision granite, and groups other samples of this interval close to the boundary between VAG/syn-COLG and WPG (Fig. 7). Similar observation may be made for three beds from the uppermost deposits of the Wapiti Formation (early Maastrichtian), bentonites P06, P07, and CUT, particularly considering the Y, Zr, TiO_2 concentrations as well as the Zr/Nb and Nb/Y ratios (Figs. 6 and 7).

6. Parent Magma composition

The chemistry of the parent volcanic rock strongly influences the type and composition of derivative products (Christidis, 1998). Nevertheless, as for the case of Grande Prairie samples, the alteration-driven introduction of selected elements might influence the composition of the volcanic beds, and consequently the estimated parent rock composition. XRF and XRD databases and field observations show that extensive low temperature hydration accompanied the devetrification of the original volcanic glass. As pointed out by Thomas et al. (1990), in similar conditions major oxides (including SiO_2, K_2O, and N_2O) and trace elements (such as Ba, Rb, S, and Sr) can be expected to have been mobilized and hence be problematic for geochemical classification.

Following the Winchester and Floyd (1977) classification model ($Zr/(TiO_2*0.0001)$ vs Nb/Y), the samples fall predominantly in the trachyandesitic (n=10), and rhyolitic (n=6) fields, with a few rhyodacitic/dacitic cases (Fig. 7A). Following Pearce et al. (1984), and Thomas et al. (1990), incompatible trace elements (Nb vs Y, and Rb vs Y+Nb) were used to infer the tectonic setting of parental volcanic rocks. In fact, increasing Zr/TiO2 and Nb/Y ratios reflect an increase in the rhyolitic character and alkalinity respectively. According to discrimination diagrams after Pearce et al. (1984) four samples (HB2, KHT, PC, and P06) fall in the within-plate granites field (WPG), whereas the remnants plot in the volcanic arc granite field (VAG), thus indicating the derivation of products from intermediate to acid volcanism (Fig. 7B). The ratio between Nb and Y varies from 0.29 to 1.2 with the highest values of Nb represented by samples WM, HB2, WP2, P07, and CUT. High concentrations of this element are found in late stage magmatic differentiates, and felsic igneous rocks generally have the highest contents (D'Argenio et al., 1994).

Following Thomas et al. 1990, multi-element diagram normalized against Ocean Ridge Granite (ORG, Pearce et al., 1984; see also Taylor and McLennan, 1995) shows that Rb, Ba, and Th are systematically enriched in the bentonite deposits, whereas Zr and Y are relatively depleted (Fig. 8A). Barium (range 110.6-2280.2; av. 810.2, ppm) and Th (range 3.5-53.6; av. 27.38 ppm) are enriched in all samples. The Ba^{2+} ion, because of it radius/valence, is more concentrated in felsic components of magmas in the later stages of crystallization and also substitutes for Ca^{2+} in plagioclase, pyroxenes and amphibole, and in the non-silicate minerals apatite and calcite. In sedimentary rocks the concentration of Ba is also related to the abundance of K-feldspar, clay minerals and hydrous Fe and Mn oxides, on to which the element may be adsorbed. Thorium is generally enriched in granitic igneous products; in sedimentary rocks, Th is essentially resistate in character, as its major host minerals, such as monazite and zircon, are highly resistant to both chemical and physical breakdown. Values of Ba and Th in all Grande Prairie samples are comparable to those reported for the Plateau Tuff in Dinosaur Provincial Park of Southern Alberta (Thomas et al., 1990, Fig. 12, p. 152). However, the abundance of these elements suggests a secondary introduction. A comparison with element concentrations of the Plateau Tuff in southern Alberta (Thomas et al., 1990) and four bentonite beds from the Two Medicine Formation of Montana (Foreman et al., 2008), show similarities between Wapiti and Montana samples, whereas Plateau Tuff volcanic ash has lower values for all parameters (Fig. 8B). However, it must be noticed that the Wapiti and Montana data are of different bentonitic beds (21 and 4 respectively), whereas element concentrations for the Plateau Tuff reflect sampling of the same layer at different localities.

7. Marker beds

Outcrop descriptions were combined with subsurface geophysical data (gamma ray well log) to document geometries and thickness variations of bentonitic beds that also represent key marker bed within the Puskwaskau and Wapiti successions (Fig. 9). Gamma ray response to altered volcanic ashes commonly results in a prominent shift toward the right in the log curve (higher values in API - American Petroleum Institute - units). Among samples reported in this study, three beds represent the final product of important volcanic events responsible of remarkable volume of falling tephra. These layers also present 1) a peculiar gamma ray signature, 2) vast lateral extent, and 3) a distinctive geochemical and mineralogical “fingerprint”. Therefore, they are candidates as potential marker beds at a regional scale. In stratigraphic order, these are the Puskwaskau bentonite (PSK), Horizon B (including HB1 and HB2), and the Wapiti River Bridge bentonite (WRB). The estimated volume of bentonitic material preserved in these layers is close to 70 cubic kilometers, also making these deposits of interest for their economical potential (see also Pyle, 1989; 1995).

7.1 Puskwaskau bentonite (PSK)

The Puskwaskau bentonite (PSK) lies within dark, organic-rich shales of the uppermost Puskwaskau Formation (Hu, 1997; Dawson, 1994a; Leckie et al., 1994) and is associated with shallow marine deposits characterized by high coastal influence as indicated by the presence of frequent tempestites and bioclastic layers (Figs. 2 and 3). PSK consists of a couplet of yellow, sulfur rich, altered volcanic ash beds separated by ~60 cm of shale. The lower horizon is strongly discontinuous on a large scale, lenticular in overall shape, and is less than 5 cm thick, whereas the upper horizon is tabular, laterally persistent, and has an overall thickness of 40 cm. Both beds crop out in the eastern flank of the Smoky River between the confluence of Kleskun Creek and the Puskwaskau River, approximately 50 meters below the basal contact of the Wapiti Formation (Fig. 2). Field observations and laboratory analyses show that the original PSK volcanic ash has been particularly subjected to alteration processes. MgO content is 4.35 wt%, whereas K_2O+Na_2O only amount to 0.86 wt%. The combination of loss of alkalis and high Mg-mobilization thus resulted in the formation of Al-smectite and montmorillonite, as indicated by XRD analysis (Fig. 10). Among the trace elements, the PSK contains anomalously high concentrations of S (15130 ppm) and high LOI value (23.33 wt%). Both values are greatest in organic- and carbonate-rich sediments, characteristics that have been documented at the sampling locality. Rhyodacitic-dacitic composition is indicated from Winchester and Floyd diagrams (Fig. 7A).

The PSK bed has been traced using geophysical well logs over an area of approximately 11,000 km^2. Therefore, considering a documented average thickness of 40 cm, this layer contains approximately 4.5 cubic kilometers of ejected volcanic material.

7.2 Horizon B (HB1 and HB2)

Horizon B occurs approximately 285 meters above the base of the Wapiti Formation and crops out extensively on the south flank of the Wapiti River, upstream from the Bear Creek confluence (Fig. 3). This marker bed consists of two distinct bentonite beds separated by a 10 cm thick, organic-rich, highly rooted mud layer. At the sampling locality, the lower volcanic layer (HB1) consists of 325 cm of light olive, structureless bentonite with frequent coalified roots preserved in the uppermost 10 cm. In contrast, the upper volcanic ash (HB2) is dark greenish gray and has an overall thickness of 160 cm. This succession also explains the peculiar double-peaked signature in the gamma ray response that characterizes this marker bed (Fig. 9). The presence of abundant paleosol-related roots at the top of HB1 and in the mud layer that separates the two bentonites indicates a gap between the two beds, supporting a different origin for these deposits. HB1 and HB2 also differ in their major oxide and particularly trace-elements concentrations. As a result, Winchester and Floyd discrimination diagrams for original magmatic composition places HB1 and HB2 within tholeiitic and trachyandesitic fields respectively (Fig. 7A). Incompatible trace element plots also indicate a volcanic arc granite origin for HB1 and within-plate granite derivation for HB2. Nevertheless almost identical Zr/Nb ratios (Zr/Nb_{HB1}= 3.97; Zr/Nb_{HB2}= 3.58) may suggest that these ash deposits were derived from a common magmatic source. XRD analyses also confirm a different diagenetic evolution of these beds: HB1 contains both illite and smectite (IL<SM) along with kaolinite and abundant K-feldspar, whereas HB2 has higher smectite, lacks kaolinite, and contains minor calcite concentration (Fig. 10).

Based on the analysis of 190 well logs, Horizon B (considering HB1 and HB2 as a single marker) is distributed over an area of approximately 10,800 km^2. It has an average thickness of 4 meters indicating a remarkable volume of tephra fell in northwestern Alberta during the volcanic event. Considering that the lateral limits of Horizon B are unknown to date, we can estimate for the study area a volume of volcanic ash deposited close to 54 km^3 (HB1~36 km^3; HB2~18 km^3). The only known late Cretaceous volcanic ash deposits with comparable volume and thickness is the late Campanian (73,5 Ma) Dorothy Bentonite that crops out in south-central Alberta (Lerbekmo, 2002; Pyle, 2003). However, it must be noted that the Dorothy bentonite, which locally reaches 13 m in thickness, represents a case of secondary thickening of the original ash fall and is preserved within the marine Bearpaw shale (high probability of preservation). In contrast, Horizon B is associated with alluvial plain and channel facies, where reduced preservation potential can be predicted.

7.3 Wapiti River Bridge bentonite (WRB)

This dark greenish grey bentonite occurs along the right side of the Wapiti River south of the town of Grande Prairie. This layer measures 94 cm in thickness at the sampling locality and crops out approximately 350 m above the base of the Wapiti Formation in association with organic rich mudstone and coal seams up to 50 cm thick. Geochemical analyses (Table 2) yield SiO_2/Al_2O_3 ratio of 3.6 and a K_2O+Na_2O value of 3.21 wt%; barium is particularly abundant (1258 ppm), whereas Nb and Y contents are low (7.1 and 13.4 ppm respectively). With respect to other samples with comparable major oxides contents, the WRB presents significantly low values of several trace elements such as Co, Mo, Nb, Pb, Rb, S, Sr, Th, Y, and Zr (see Table 2); only Cr is enriched. WRB bentonite falls in the dacite field, whereas the Nb/Y discrimination diagram indicates volcanic arc to syn-collisional granite composition (Fig. 7A).

The gamma ray peak that typifies WRB is the most characteristic among the marker beds, ranging between 170 and 185 API units. As for other marker beds, its persistence has been documented over the entire study area, with the exception of local cuts due to the presence of erosive channel deposits. Based on an average thickness of 90 cm, WRB bentonite consists of approximately 10 cubic kilometers of altered volcanic material.

8. Comparison with Western Interior Basin bentonites

Geochemical features of the volcanic ashes studied here were compared to those reported in the literature for time equivalent bentonites of central and southern Alberta (Lerbekmo, 1968, 2002; Thomas et al., 1990), Manitoba (Cadrin et al, 1995), and Montana (Foreman et al., 2008) with the aim of testing the presence of possible time or space relationship (Table 3). The dataset available in the literature, however, do not provide complete information on trace elements and therefore TAS diagrams were adopted for comparisons instead of the Zr-Nb/Y plot. To test this hypothesis, 51 bentonites (study area, n=21, central and southern Alberta, n=24; Montana, n=4; Manitoba, n=2) were first divided by age into three groups: pre-Bearpaw, syn-Bearpaw, and post-Bearpaw (Fig. 11). Of remarkable importance, available data on SiO_2 contents from this study and from Lerbekmo (1968) clearly indicate a sequential and gradual change toward more siliceous volcanism from the late Campanian onward. The average SiO_2 wt% increases from 56.6 in the Belly River Group and lower Wapiti Formation (see Fig. 1) to 61 in the Bearpaw Formation and equivalent, and 63.7 in the Edmonton Group and upper Wapiti Formation. In the latter stratigraphic interval (latest Campanian-lower Maastrichtian), SiO_2 contents reach values of 72.3%. Furthermore, the TAS diagrams indicate that pre-Bearpaw (>74 Ma) bentonites fall predominantly in the andesite and basaltic andesite fields, whereas syn- and post-Bearpaw ash beds (<74 Ma) are predominantly andesitic and dacitic, along with a few rhyolites. This trend toward more acidic products is associated with a decrease in average total alkali contents, from 3.08 wt% in pre- and syn-Bearpaw bentonites to 2.57 wt% in post-Bearpaw ashes. Therefore, despite the fact Grande Prairie samples show a trend toward lower SiO_2 values (from 61.2 wt% to 55.3 wt%) from the early Maastrichtian (Fig. 6), this study supports previous observations on bentonite beds from western Alberta by Lerbekmo (1968; see also Lerbekmo, 2002; Thomas et al., 1990).

Cinerites were then gathered into six distinctive geographical areas: 1- Montana, 2- Southern Alberta, 3- Central Alberta, 4– Western Alberta, 5– Grande Prairie, and 6– Manitoba (Figs. 12 and 13). Along the eastern margin of the Cordillera, samples from Montana and Southern Alberta are relatively well confined to the andesitic and basaltic-andesitic fields whereas bentonites from central Alberta are characterized by diverse compositions with samples representative of all subalkaline series, with most samples falling in the basaltic-andesite field. Cinerites from western Alberta and the Grande Prairie area have predominantly dacitic affinities; interestingly, samples from western Alberta have lower total alkali contents than those from Grande Prairie region.

Lastly, the two samples reported from Manitoba fall in the basaltic-andesite field and have remarkably low alkali contents, possibly due to local alteration processes.

9. Source of the Wapiti Formation bentonites

Continental-arc magmatism took place along much of the western North America Cordillera during the late Cretaceous and early Tertiary. As a result, volcanoclastic materials or their diagenetic derivates (bentonites, bentonitic mudstones and sandstones, detrital, and volcanic rock fragments) are extremely common within both marine and terrestrial late Cretaceous Western Interior basin successions. Such deposits and their geochemical, stratigraphic, and petrographic importance have been documented in the literature (Lerbekmo, 1968; McLean, 1971; Mack and Jerzykiewicz, 1989; Thomas et al., 1990; Eberth and Hamblin, 1993; Cadrin et al., 1995; Bertog and Huff, 1999; Roberts and Hendrix, 2000; Payenberg et al., 2002; Eberth, 2005; Roberts et al., 2005; Foreman et al., 2008). However, the occurrence of different volcanic centers of late Cretaceous age of comparable scattered composition along a 2500 km long mountain belt led to diverse approaches to locate potential source areas. For example, Thomas et al. (1990) indicated the Elkhorn Mountains Volcanics complex was the most convincing source of the Plateau Tuff (Dinosaur Park Formation, southeast Alberta) on the basis of geochemical affinities, and Lerbekmo (2002) reconstructed the dispersal of the Dorothy Bentonite (southern Alberta) using an isopach map based on subsurface and surface thickness measurements from the Howell Creek Intrusive area (southern British Columbia; see also Bowerman et al., 2006 for geochemical characterization of the Howell Creek suite).Bentonite layers of the Two Medicine Formation (Montana) are commonly referred to the Elkhorn and Adel Mountain Volcanic complexes, based on sedimentological and stratigraphic data and high resolution age control (Rogers et al., 1993; Roberts and Hendrix, 2000; Foreman et al., 2008).

At the time of the deposition of the Wapiti succession, British Columbia was subject to arc events with the emplacement of several volcanic complexes. Among those, the Windy-Table suite, the Fawnie Range (Nechako Plateau), and the Buck Creek Complex (Fig. 13) have ages and compositions fro appropriate comparison with the Grande Prairie cinerites. Rocks included in the Windy-Table suite (northwestern British Columbia) are dominantly felsic, characterized by quartz-phyric ash flow units, and were emplaced between 81.3 and 72.4 Ma (Grond et al., 1984; Mihalynuk and Smith, 1992; Mihalynuk, 1999). The Fawnie Range of the Nechako Plateau of central British Columbia documents late Cretaceous (74-66 Ma) continental arc activity characterized by andesitic volcanic rocks with rare rhyolites (Friedman et al., 2001; Whalen et al., 2001). Finally, the Buck Creek Complex produced a major pulse of volcanism between 85 and 73 Ma (Church, 1973; Leitch et al., 1992) responsible for extrusion of continental margin calc-alkaline basaltic andesites to rhyolites (Dostal et al., 2005). Available geochemical data for Cretaceous volcanic products of these volcanic complexes (including major- and trace-elements), indicate that the Nechaco Plateau and related batholites of central British Columbia are the best candidates as sources for the bentonites described in this study (Friedman et al., 2001; Whalen et al., 2001; Edwards and Bye, 2003; Dostal et al., 2005).

However, as pointed by Thomas et al. (1990), further considerations should include paleogeographic and palinspastic reconstructions (in order to estimate the distance between source area and depocenter), and paleowind directions. Observations on lateral geometries of beds indicate that the bentonite layers gradually increase in thickness toward the west-south west. This is consistent with previous studies, indicating that during the late Cretaceous the main wind directions were westerly at a latitude close to 60° north. Models thus suggest that volcanic ashes that originated in the westernmost regions of the Canadian Cordillera would have been transported west-east across British Columbia and Alberta, and then north west - southeast toward Saskatchewan and Manitoba across the Western Interior seaway (Lloyd, 1982; Elder, 1988, Thomas et al., 1990). Approximate present-day distance between the central British Columbia volcanic complexes and the study area is 500 km. Comparable or larger distance between the source areas and the sedimentary basin during the late Cretaceous is supported by the homogeneous fine granulometry (clay) of cineritic deposits preserved in both the Puskwaskau and Wapiti successions.

10. Conclusions

This study represents a detailed analysis of twenty-one bentonites from the late Cretaceous Puskwaskau and Wapiti formations of northwestern Alberta. Although volcanic ashes examined have been significantly altered by processes including weathering, percolating groundwater, and localized hydrothermal activities, geochemical and stratigraphic analyses suggest that these beds provide useful information for comparing the Grande Prairie deposits with other known successions of the Western Interior Basin. Geochemical analyses indicate that original magmatic composition were largely rhyolitic to trachyandesitic; trace-element discrimination data suggest a volcanic arc to within-plate tectonic setting for the parent eruptive centers. Moreover, the XRF data strongly suggest the presence of multiple source areas with different magmatic compositions that resulted in a bimodal occurrence of basic and acidic volcanic ashes. Among the potential locations for source eruptive centers, the Nechaco Plateau and related batholites of central British Columbia represent the best candidates on the base of geochemical affinities, timing of volcanic activity, and distance from the depocenter.

Comparisons with other known bentonite beds from Alberta, Montana, and Manitoba, encompassing approximately 1000 km north-south of the Western Interior Basin, do indicate the presence of geographical variation in the geochemical composition of volcanic products along the Canadian cordillera. Similarly, from a time-related prospective this study supports a gradual shift toward more siliceous and alkali-depleted products from the late Campanian onward (top of the Belly River Group). Therefore, geochemical analyses of bentonite beds of the Western Interior Basin deposits in Canada and northern U.S. allow the identification of both stratigraphic and geographic trends: such data, supported by detailed petrographic and radioisotopic information, may greatly improve further studies on the evolution of the sedimentary basin and on correlation between coeval successions. Of paramount importance, such methodologies are suitable for entirely non-marine successions, as in the study case of the Late Cretaceous Wapiti Formation. The correlation of such intervals within the foreland basin of Alberta provide an important case study in the analysis of foreland basins, and may shed light on the relationships between orogenic phases and related volcanic arc pulses, variations in basin subsidence and depocenter migration.

Finally, three discrete bentonitic beds (PSK, Horizon B, and WRB) are potentially a promising tool for regional correlation on the light of distinctive geochemical composition and gamma-ray response in subsurface: in particular, Horizon B may represent a litho- and chronostratigraphic marker horizon of regional significance. Radioisotopic dating and detailed chemical and mineralogical analyses of these layers at different localities southward along the margin of the cordillera offer the best prospects for successful correlation. Their stratigraphic occurrence and distribution suggest restricted time intervals (< 1Ma) of intense eruptive activity in the Cordillera volcanic centers, particularly in concomitance with the Bearpaw seaway transgressive and regressive phases, and in the uppermost deposits of the Wapiti Formation (lower Maastrichtian).

Acknowledgements

This research was conducted as part of the author's Ph.D. dissertation at the Department of Earth and Geoenvironmental Sciences of the University of Bologna, in collaboration with the University of Alberta (Edmonton, Canada). The author wish to thank Katalin and Nick Ormay, Robert Hunt, Sheldon Graber, Desh Mittra, Roy Bickle, and the Grande Prairie Regional College for their fundamental involvement and support at every stage of this project. I wish to thank Giovanna Sapienza for enlightening discussions that greatly improved this manuscript. I am also indebted to Tetsuto Miyashita, Paul McNeil, Larry Hodges, and Jim Parker for their precious help in the field. Comments from G. J. Weltje (Delft University of Technology, The Netherlands), John Berkley (Suny University, Fredonia, NY), and Barry Roser (Shimane University, Japan) greatly improved this study. Finally, I wish to thank Octavian Catuneanu, Gian Battista Vai, Alceo Mordenti, David Eberth, Enrico Dinelli, and Francesco Dellisanti for their help at various stages of the project. This research was financially supported by the University of Bologna, the Giovanni

Capellini Museum of Geology and Palaeontology (Bologna), the Dinosaur Research Institute, and The Jurassic Foundation.

References

Allan, J., Carr, J., 1946. Geology and coal occurrences of Wapiti-Cutbank area, Alberta. Research Council of Alberta, Report 48, 50 pp.

Armstrong-Altrin J., Lee, Y., Verma, S., and Ramasamy, S., 2004. Geochemistry of Sandstones from the Upper Miocene Kudankulam Formation, Southern India: Implications for Provenance, Weathering, and Tectonic Setting. Journal of Sedimentary Research 74, 285-297.

Baadsgaard, H., Lerbekmo, J., Wijbrans, J., 1993. Multimethod radiometric age for a bentonite near the top of the *Baculites reesidei* Zone of southwestern Saskatchewan (Campanian-Maastrichtian stage boundary?). Canadian Journal of Earth Sciences 30, 769-775.

Bates, R., Jackson, J., 1987. Glossary of Geology, Third Edition. American Geological Institute Alexandria, Virginia, 788 pp.

Bertog, J., 1999. Biotite geochemistry of the bentonites in the Sharon Spring Member of the Pierre Shale (Campanian, Late Cretaceous): their use in magmatic interpretation and stratigraphic correlation. Abstracts With Programs - Geological Society of America 31, pp. 233.

Bertog, J., Huff, W.,1999. Biotite geochemistry of the bentonites in the Sharon Spring member of the Pierre Shale (Campanian, Late Cretaceous): their use in magmatic interpretation and stratigraphic correlation. Abstract with Programs. Geological Society of America 31, pp. 233.

Bowerman, M., Christianson, A., Creaser, R., Luth, R., 2006. A petrological and geochemical study of the volcanic rocks of the Crowsnest Formation, southwestern Alberta, and of the Howell Creek suite, British Columbia. Canadian Journal of Earth Sciences 43, 1621-1637.

Brinkman, D., 2003. A review of nonmarine turtles from the Late Cretaceous of Alberta. Canadian Journal of Earth Sciences 40, 557-571.

Byrne, P., 1955. Bentonite in Alberta. Research Council of Alberta, Report 71, 20 pp.

Cadrin, A., Kyser, T., Caldwell, W., Longstaffe, F., 1995. Isotopic and chemical compositions of bentonites as paleoenvironmental indicators of the Cretaceous Western Interior Seaway. Palaeogeography, Palaeoclimatology, Palaeoecology 119, 301-320.

Carter, J., 1957. Final geological report on bentonite, Grande Prairie, Alberta. Mineral Assessment Report 19570016, 3 pp.

Christidis, G., 1998. Comparative study of the mobility of major and trace elements during alteration of an andesite and a rhyolite to bentonite, in the islands of Milos and Kimolos, Aegean, Greece. Clays and Clay Minerals 46, 567-594.

Christidis, G., 2001. Geochemical correlation of bentonites from Milos Island, Aegean, Greece. Clay Minerals 36, 295-306.

Church, B., 1973. Geology of the Buck Creek area. Geology exploration and mining 1972: Victoria, BC. British Columbia Ministry of Energy, Mines, and Petroleum Resources, 353–363.

Curzi, P., Dinelli, E., Ricci Lucchi, M., Vaiani, S., 2006. Palaeoenvironmental control on sediment composition and provenance in the late Quaternary deltaic successions: a case study from the Po delta area (Northern Italy). Geological Journal 41, 591-612.

D'Argenio, B., Innocenti, F., Sassi, F., 1994. Introduzione allo studio delle rocce. UTET, Torino, pp. 155.

Dawson, F., Evans, C., Marsh, R., Richardson, R., 1994a. Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin. In: Mossop, G., Dixon, J. (Eds.). Geological Atlas of the Western Canada Sedimentary Basin. Alberta Geological Survey, 18 pp.

Dawson, F., Kalkreuth, W., Sweet, A., 1994b. Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta. Geological Survey of Canada Bulletin 466, 60 pp.

Desmares, D., Beaudoin, B., Grosheny, D., Lafaye, F., Stille, P., 2002. High-resolution variability of stratigraphic records constrained by volcanic ashes: the Cenomanian-Turonian boundary in the Western Interior Basin. Abstracts With Programs - Geological Society of America 34, pp. 135.

Desmares, D., Grosheny, D., Beaudoin, B., Gardin, S., Gauthier-Lafaye, F., 2007. High resolution stratigraphic record constrained by volcanic ash beds at the Cenomanian-Turonian boundary in the Western Interior Basin, USA. Cretaceous Research 28, 561-582.

Dostal, J., Church, B., Hamilton, T., 2005. Episodic volcanism in the Buck Creek Complex (Central British Columbia, Canada): a history of magmatism and mantle evolution from the Jurassic to the Early Tertiary. International Geology Review 47, 551-572.

Eberth, D., 1990. Stratigraphy and sedimentology of vertebrate microfossil sites in the uppermost

Judith River Formation (Campanian), Dinosaur Provincial Park, Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 78, 1-36.

Eberth, D., 2002. Review and comparison of Belly River Group and Edmonton Group Stratigraphy and stratigraphic architecture in the southern Alberta Plains. CSPG Diamond Jubilee Convention, Program and Abstract 117.

Eberth, D., 2005. The geology. In: Currie, P., Koppelhus, E. (Eds.). Dinosaur Provincial Park, a spectacular ancient ecosystem revealed. Indiana University Press, Bloomington, 54-82.

Eberth, D., Brinkman, D., 1997. Paleoecology of an estuarine, incised-valley fill in the Dinosaur Park Formation (Judith River Group, Upper Cretaceous) of southern Alberta, Canada. Palaios 12, 43-58.

Eberth, D., Deino, A., 1992. A geochronology of the nonmarine Judith River Formation of southern Alberta. SEPM Theme Meeting, Mesozoic of the Western Interior, 24-25.

Eberth, D., Hamblin, A., 1993. Tectonic, stratigraphic, and sedimentologic significance of a regional discontinuity in the upper Judith River Group (Belly River wedge) of southern Alberta, Saskatchewan, and northern Montana. Canadian Journal of Earth Sciences 30, 174-200.

Edwards, B., Bye, A., 2003. Preliminary results of field mapping, GIS spatial analysis, and major element geochemistry, Ruby Mountain volcano, Atlin volcanic district, northwestern British Columbia. Geological Survey of Canada, Current Research 2003 – A10.

Elder, W., 1988. Geometry of upper Cretaceous bentonite beds: implications about volcanic source areas and paleowind patterns, Western Interior, United States. Geology 16, 835-838.

Fanti, F., 2007. Unfolding the geological history of the North: new comprehensive survey of the Wapiti Formation, Alberta, Canada. In: Braman, D. (Ed.). Ceratopsian Symposium, Short Papers, Abstracts and Programs, 33-38.

Foreman, B., Rogers, R., Deino, A., Wirth, K., Thole, J., 2008. Geochemical characterization of bentonite beds in the Two Medicine Formation (Campanian, Montana), including a new $^{40}Ar/^{39}Ar$ age. Cretaceous Research 29, 373-385.

Fralick, P., Kronberg, B., 1997. Geochemical discrimination of clastic sedimentary rock sources. Sedimentary Geology 113, 111–124.

Franzini, M., Leoni, L., Saitta, M., 1972. A simple method to evaluate the matrix effects in X-Ray fluorescence analysis. X-Ray Spectrometry 1, 151-154.

Franzini, M., Leoni, L., Saitta, M., 1975. Revisione di una metodologia analitica per fluorescenza-X, basata sulla correzione completa degli effetti di matrice. Rend. Soc. It. Min. Petrol. 31, 365-378.

Friedman, R., Diakow, L., Lane, R., Mortensen, J., 2001. New U-Pb age constraints on latest Cretaceous magmatism and associated mineralization in the Fawnie Range, Nechako Plateau, central British Columbia. Canadian Journal of Earth Sciences 38, 619-637.

Geo-Engineering (M.S.T.) Ltd., 2005. Pipestone Creek Interpretive Centre, Phase 1, geotechnical investigation. Unpublished report submitted to the County of Grande Prairie, available online at www.gprc.ab.ca/community/pipestone/3227%20R02%Phase%20I%20-%20Investigation%20Report%20(1).pdff

Goodwin, M., Deino, A., 1989. The first radiometric ages from the Judith River Formation (Upper Cretaceous), Hill Country, Montana. Canadian Journal of Earth Sciences 26, 1384-1391.

Grim, R., Guven, N., 1978. Bentonites: geology, mineralogy, properties, and use. Developments in Sedimentology 24, Elsevier Publishing Company, New York, 256 pp.

Grond, H., Churchill, S., Armstrong, R., Harakal, J., Nixon, G., 1984. Late Cretaceous Age of the Hutshi, Mount Nansen, and Carmacks groups, Southwestern Yukon Territory and Northwestern British Columbia. Canadian Journal of Earth Sciences 21, 554-558.

Hicks, J., Obradovich, J., Tauxe, L., 1995. A new calibration point for the Late Cretaceous time scale: the $^{40}Ar/^{39}Ar$ isotopic age of the C33r/C33n geomagnetic reversal from the Judith River Formation (Upper Cretaceous), Elk Basin, Wyoming, USA. Journal of Geology 103, 243-356.

Hicks, J., Obradovich, J., Tauxe, L., 1999. Magnetostratigraphy isotopic age calibration and intercontinental correlation of the Red Bird section of the Pierre Shale, Niobara County, Wyoming, USA. Cretaceous Research 20, 1-27.

Hu, Y., 1997. High-resolution sequence stratigraphic analysis of the Upper Cretaceous Puskwaskau Formation of west-central Alberta and adjacent British Columbia: outcrop and subsurface. PhD thesis, Faculty of Graduate Studies, The University of Western Ontario, London, Ontario.

Irvine, T., Baragar, W., 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences 8, 523-548.

Jerzykievicz, T., Norris, D., 1994. Stratigraphy, structure and syntectonic sedimentation of the

Campanian "Belly River" clastic wedge in the southern Canadian Cordillera. Cretaceous Research 15, 367-399.

Le Bas, M., Le Maitre, L., Streckeisen, A, Zanettin, B., 1986. A chemical classification of volcanic rocks based on the Total Alkali-Silica diagram. Journal of Petrology 27, 745-750.

Leckie, D., Bhattacharya, J., Bloch, J., Gilboy, C., Norris, B., 1994. Cretaceous Colorado / Alberta Group of the Western Canada Sedimentary Basin. In: Mossop, G., Dixon, J. (Eds.). Geological Atlas of the Western Canada Sedimentary Basin. Alberta Geological Survey, pp. 335-352.

Lehman, T., McDowell, F., Connely, J., 2006. First isotopic (U-Pb) age for the Late Cretaceous *Alamosaurus* vertebrate fauna of West Texas, and its significance as a link between two faunal provinces. Journal of Paleontology 26, 922-928.

Leitch, C., Hood, C., Cheng, X., Sinclair, A., 1992. Tip Top Hill volcanics: Late Cretaceous Kasalka Group rocks hosting epithermal base- and precious-metal veins at Owen Lake, west-central British Columbia. Canadian Journal of Earth Sciences 29, 854–864.

Leoni, L., Saitta, M., 1976. X-ray fluorescence analysis of 29 trace elements in rock and mineral standard. Rend. Soc. It. Min. Petrol. 32, 497-510.

Leoni, L., Manichini, M., Saitta, M., 1982. Determination of S, Cl, and F in silicate rocks by X-Ray fluorescence analyses. X-Ray Spectrometry 11, 156-158.

Lerbekmo, J., 1968. Chemical and modal analyses of some Upper Cretaceous and Paleocene bentonites from western Alberta. Canadian Journal of Earth Sciences 5, 1505-1511.

Lerbekmo, J., 2002. The Dorothy bentonite: an extraordinary case of secondary thickening in a late Campanian vocanic ash fall in central Alberta. Canadian Journal of Earth Sciences 39, 1745-1754.

Lloyd, C., 1982. the mid-Cretaceous earth: paleogeography; ocean circulation and temperature; atmospheric circulation. Journal of Geology 90, 393-413.

Mack, G., Jerzykiewicz, T., 1989. Provenance of post-Wapiabi sandstones and its implications for Campanian to Paleocene tectonic history of the southern Canadian Cordillera. Canadian Journal of Earth Sciences 26, 665-676.

McLean, J., 1971. Stratigraphy of the Upper Cretaceous Judith River Formation in the Canadian Great Plains. Saskatchewan Research Council, Geology Division Report 11, 96 pp.

Mihalynuk, M., 1999. Geology and mineral resources of the Tagish Lake area (NTS 104M/8,9,10E, 15 and 104N/12W) Northwestern British Columbia. British Columbia Ministry of Energy and Mines, Bulletin 105, 85-95.

Mihalynuk, M., Smith, M., 1992. Highlights of 1991 mapping in the Atlin-west map area (104N/12). In: Grant, B., Newell, J. (Eds.). Geological Fieldwork 1991 B.C. Ministry of Energy, Mines and Petroleum Resources, Paper 1992-1, 221-227.

Obradovich, J., 1993. A Cretaceous time scale. In: Caldwell, W., Kauffman, E. (Eds.). Evolution of the Western Interior Basin. Geological Association of Canada Special Paper 39, 379-396.

Obradovich, J., Cobban, W., 1975. A time-scale for the Late Cretaceous of the Western Interior of North America. In: Caldwell, W. (Ed.). The Cretaceous system in the Western Interior of North America. Geological Association of Canada Special Paper 13, 31-54.

Payenberg, T., Braman, D., Davis, D., Miall, A., 2002. Litho- and chronostratigraphic relationships of the Santonian-Campanian Milk River Formation in southern Alberta and the Eagle Formation in Montana utilising stratigraphy, U-Pb geochronology, and palynology. Canadian Journal of Earth Sciences 39, 1553-1577.

Pearce, J., Jarvis, I., 1992. Applications of geochemical data to modelling sediment dispersal patterns in distal turbidites: late Quaternary of the Madeira Abyssal Plain. Journal Sedimentary Petrology 62, 1112–1129.

Pearce, J., Harris, N., Tindle, A., 1984. Trace elements discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology 25, 956-983.

Pearce, J., Beasly, B., Wray, D., Wright, D., 1999. Chemostratigraphy: a method to improve interwell correlation in barren sequences-case study using onshore Duckmantian/Stephanian sequences (West Midlands, UK). Sedimentary Geology 124, 197–220.

Peccerillo, A., Taylor, S., 1976. Geochemistry of Eocene Calc-Alkaline Volcanic Rocks from the Kastamonu Area, Northern Turkey. Contribution to Mineralogy and Petrology 58, 63-81.

Pellenard, P., Deconinck, J-F., Huff, W., Thierry, J., Marchand, D., Fortwengler, D., Trouiller, A., 2003. Characterization and correlation of Upper Jurassic (Oxfordian) bentonite deposits in the Paris Basin and the Subalpine Basin, France. Sedimentology 50, 1035-1060.

Pyle, D., 1989. The thickness, volume and grain size of tephra fall deposits. Bulletin of Volcanology 51, 1-15.

Pyle, D., 1995. Assessment of the minimum volume of tephra fall deposits. Journal of Volcanology and Geothermal Research 69, 379-382.

Pyle, D., 2003. Discussion of “The Dorothy Bentonite: an extraordinary case of secondary thickening in a late Campanian volcanic ash fall in central Alberta". Canadian Journal of Earth Sciences 40, 1169-1170.

Roberts, E., Hendrix, M., 2000. Taphonomy of a petrified forest in the Two Medicine Formation (Campanian), Northwest Montana: implications for palinspastic restoration of the Boulder batholith and Elkorn Mountain volcanics. Palaios 15, 476-482.

Roberts, E., Deino, A., Chan, M., 2005. $^{40}Ar/^{39}Ar$ age of the Kaiparowits Formation, southern Utah, and correlation of contemporaneous Campanian strata and vertebrate faunas along the margin of the Western Interior Basin. Cretaceous Research 26, 307-318.

Roen, J., Hosterman, J., 1982. Misuse of the term bentonite for ash beds of Devonian age in the Appalachian basin. Geological Society of America Bulletin 93, 921-925.

Rogers, R., Swisher III ,C., Horner, J., 1993. $^{40}Ar/^{39}Ar$ age and correlation of the nonmarine Two Medicine Formation (Upper Cretaceous), northwestern Montana, U.S.A. Canadian Journal of Earth Sciences 30, 1066-1075.

Rutherford, R., 1930. Geology and water resources in parts of the Peace River and Grande Prairie Districts, Alberta. Research Council of Alberta, Report 21, 68 pp.

Schnurr, W., Trumbull, R., Clavero, J., Hahne, K., Siebel, W., Gardeweg, M., 2007. Twenty-five million years of silicic volcanism in the southern central volcanic zone of the Andes: geochemistry and magma genesis of ignimbrites from 25 to 27 °S, 67 to 72 °W. Journal of Volcanology and Geothermal Research 166, 17-46.

Stott, D., 1961. Dawson Creek map area, British Columbia. Geological Survey of Canada Paper 61, 10 pp.

Taylor, S., McLennan, S., 1995. The geochemical evolution of the continental crust. Reviews of Geophysics 33, 241-265.

Thomas, R., Eberth, D., Deino, A., Robinson, D., 1990. Composition, radioisotopic ages, and potential significance of an altered volcanic ash (bentonite) from the Upper Cretaceous Judith River Formation, Dinosaur Provincial Park, southern Alberta, Canada. Cretaceous Research 11, 125-162.

Whalen, J., Anderson, R., Struik, L., Villeneuve, M., 2001. Geochemistry and Nd isotopes of the François Lake plutonic suite, Endako batholith: host and progenitor to the Endako molybdenum camp, central British Columbia. Canadian Journal of Earth Sciences 38, 603-619.

Williams, G., Baadsgaard, H., 1975, Potassium-argon dates and Upper Cretaceous biostratigraphy in eastern Saskatchewan. In: Caldwell, W. (Ed.). The Cretaceous system in the Western Interior of North America. Geological Association of Canada Special Paper 13,417-426.

Winchester, J., Floyd, P., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology 20, 325-343.

Zhengjun, H., Jinyi, L., Shenugo, M., Sorokin, A., 2005. Geochemical discriminations of sandstones from the Mohe Foreland basin, north-eastern China: tectonic setting and provenance. Scinece in China, Ser. D 48, 613-621.

Tables:

Table 1: List of samples discussed in this study, including abbreviation, location, thickness, and colour observed in the field.

Table 2: X-ray fluorescence analyses of bentonite samples from the uppermost Puskwaskau Formation and the Wapiti Formation in the Grande Prairie area.

Table 3: Time-space variation in bentonite bed hypothesized original composition. Results indicate a gradual shift toward more acidic products during the upper Campanian (from basaltic andesite to rhyodacite). Data also indicate the presence of south-north geographical discriminating trends in the composition of volcanic ash beds.

Figure Caption

Figure 1: Locality map of the Grande Prairie region showing sample localities. See Table 1 for sample abbreviations.

Figure 2: Stratigraphic distribution of bentonites in the Puskwaskau and Wapiti formations and representative stratigraphic columns of the most common facies associations in which the bentonites occur. B marks the occurrence of volcanic ash beds in the columns.

Figure 3: Field pictures of bentonite layers: A, Yellow, sulfur-rich bentonite PSK, Puskwaskau Formation, Smoky River; B, Carbonate cemented bentonite at the base of fine sand channel deposits, Wapiti Formation, Red Willow River. C, Horizon B (HB1 and HB2) that crop out along the Wapiti River. D, Detail of the highly rooted, organic rich mud layer overlying HB1: note the difference in color and texture between HB1 and HB2. E, Wapiti Bonebed

bentonitie (WB) occurs within wet and immature paleosols below a vast vertebrate bonebed. F, Bentonite P07 crops out along the Pinto Creek: this altered volcanic ash is located between coal seams up to 120 cm thick.

Fig. 4: A, SiO_2-K_2O classification of samples from the Grande Prairie area (Peccerillo and Taylor, 1976), and B, AFM (Irvine and Baragar, 1971) classification diagrams.

Fig. 5: A, projection of major elements over SiO_2 (Grande Prairie samples). B, projection of trace elements over Zr for their evaluation of their relative mobility during devetrification processes (Grande Prairie samples).

Fig.6: Time related variations of selected major and trace elements for Puskwaskau and Wapiti bentonites.

Fig. 7: A, Zr/TiO_2 - Nb/Y classification diagram after Winchester and Floyd (1977) showing original magmatic composition of the bentonites. B, Nb/Y discrimination diagram after Pearce et al. (1984). WPG, within-plate granite; ORG, ocean ridge granite; VAG, volcanic arc granite; syn-COLG, syn-collision granite.

Fig. 8: ORG-normalized multi-element diagram for A, Wapiti bentonite data shown in Table 2, and B, comparison of element concentrations of bentonite from Grande Prairie (this study), southern Alberta (Plateau Tuff, Thomas et al., 1990), and Montana (Two Medicine Formation, Foreman et al., 2008). Normalization values after Pearce et al. (1984).

Fig. 9: A, gamma ray signature of bentonite PSK (Puskwaskau Formation), Horizon B (HB1 and HB2), and Horizon C (WRB) of the Wapiti Formation. B, comparison between the gamma ray signature of Horizon B and an outcrop section at the sampling locality showing the distinctive double peak marked by the presence of the mud layer separating HB1 and HB2.

Fig. 10: X-Ray diffraction (XRD) traces of bentonite PSK, HB1, HB2, and WRB. K, Kaolinite; Q, quartz; Pl, plagioclase; Ca, calcite; M, montmorillonite; I/S, illite/smectite mixed layer.

Fig. 11: A, TAS diagram (after Le Bas et al., 1986) showing classification of pre-, syn-, and post-Bearpaw volcanic ashes from Alberta and Montana.

Fig. 12: TAS classification of 51 bentonites from Western Interior Basin deposits of Alberta, Montana, and Manitoba.

Fig. 13: A, present day geographic distribution of volcanic complexes (dark grey) along the Canadian Cordillera active during the deposition of the Puskwaskau and Wapiti formation, and extension of the Western Interior Basin; 1, Montana; 2, Southern Alberta; 3, Central Alberta; 4, Western Alberta; 5, Grande Prairie; 6, Manitoba. B, reconstructed distribution pattern of volcanic ash on the basis of geochemical analyses and hypothesized main wind directions during the Campanian-Maastrichtian (see the text for discussion). Black arrows indicate main wind directions.

	Horizon	GPS Location (WGS84 datum)	Average Thickness (cm)	Color (Munsell Soil Color Chart, 2000)
1	*Puskwaskau (PSK)*	Smoky River N55°29'41"; W118°08'38"	40	Yellow (2.5Y-7/6)
2	*White Mountain (WM)*	Wapiti River N54°58'16"; 119°33'86"	15	Pale yellow (5Y-7/4)
3	*Bear Creek (BC)*	Bear Creek-Wapiti River N55°06'29"; W118°28'16"	30	Greenish gray (GLEY1-5/10GY)
4	*Horizon B 1 (HB1)*	Wapiti River N55°04'49"; W118°32'11"	325	Olive (5Y-5/2)
5	*Horizon B 2 (HB2)*	Wapiti River N55°04'49"; W118°32'11"	150	Very dark greenish gray (GLEY2-3/10G)
6	*Kleskun Hill Bentonite (KHB)*	Kleskun Hill N55°15'14"; W118°30'38"	20	Olive (5Y-4/4)
7	*Lizard Hill (LH)*	Kleskun Hill N55°15'33"; 118°30'28"	40	Olive (5Y-4/4)
8	*Kleskun Hill Top (KHT)*	Kleskun Hill N55°04'28"; W118°46'28"	35	Olive (5Y-5/3)
9	*Wapiti River Bridge (WRB)*	HW40South - Wapiti Bridge N55°15'33"; W118°30'27"	96	Dark greenish gray (GLEY1-4/10Y)
10	*Spring Creek (SC)*	Spring Creek - Wapiti River N55°04'32"; W118°56'08"	35	Light olive gray (5Y-6/2)
11	*Wapiti Pipestone 1 (WP1)*	Wapiti River N55°03'02"; W119°06'47"	20	Olive gray (5Y-4/2)
12	*Wapiti Pipestone 2 (WP2)*	Wapiti River N55°02'39"; W119°06'14"	25	Olive (5Y-5/2)
13	*Pipestone Creek (PC)*	Pipestone Creek N55°02'84"; W119°06'16"	20	Pale yellow (5Y-7/4)
14	*Wapiti River (WR)*	Wapiti River N55°04'48"; W118°59'16"	15	Gray (5Y-5/1)
15	*Red Willow 2007 (RW07)*	Red Willow River N55°03'27"; W119°22'31"	20	Greenish gray (GLEY1-5/10GY)
16	*Red Willow 3 (RW3)*	Red Willow River N55°03'27"; W119°22'31"	20	Light greenish gray (GLEY1-7/5G7)
17	*George Robinson (GR)*	Red Willow River N55°02'54"; W119°59'19"	10	Greenish gray (GLEY1-5/5G)
18	*Wapiti Bonebed (WB)*	Wapiti River N54°58'16"; W119°33'86"	15	Pale yellow (5Y-7/4)
19	*Pinto Creek 2006 (P06)*	Pinto Creek N54°56'86"; W119°27'34"	5	Greenish gray (GLEY1-5/5G)
20	*Pinto Creek 2007 (P07)*	Pinto Creek N54°50'32"; W119°23'30"	15	Pale yellow (5Y-7/4)
21	*Cutbank River (CR)*	Cutbank River N54°31'36"; W118°56'43"	20	Dark gray (5Y-4/1)

Table 1

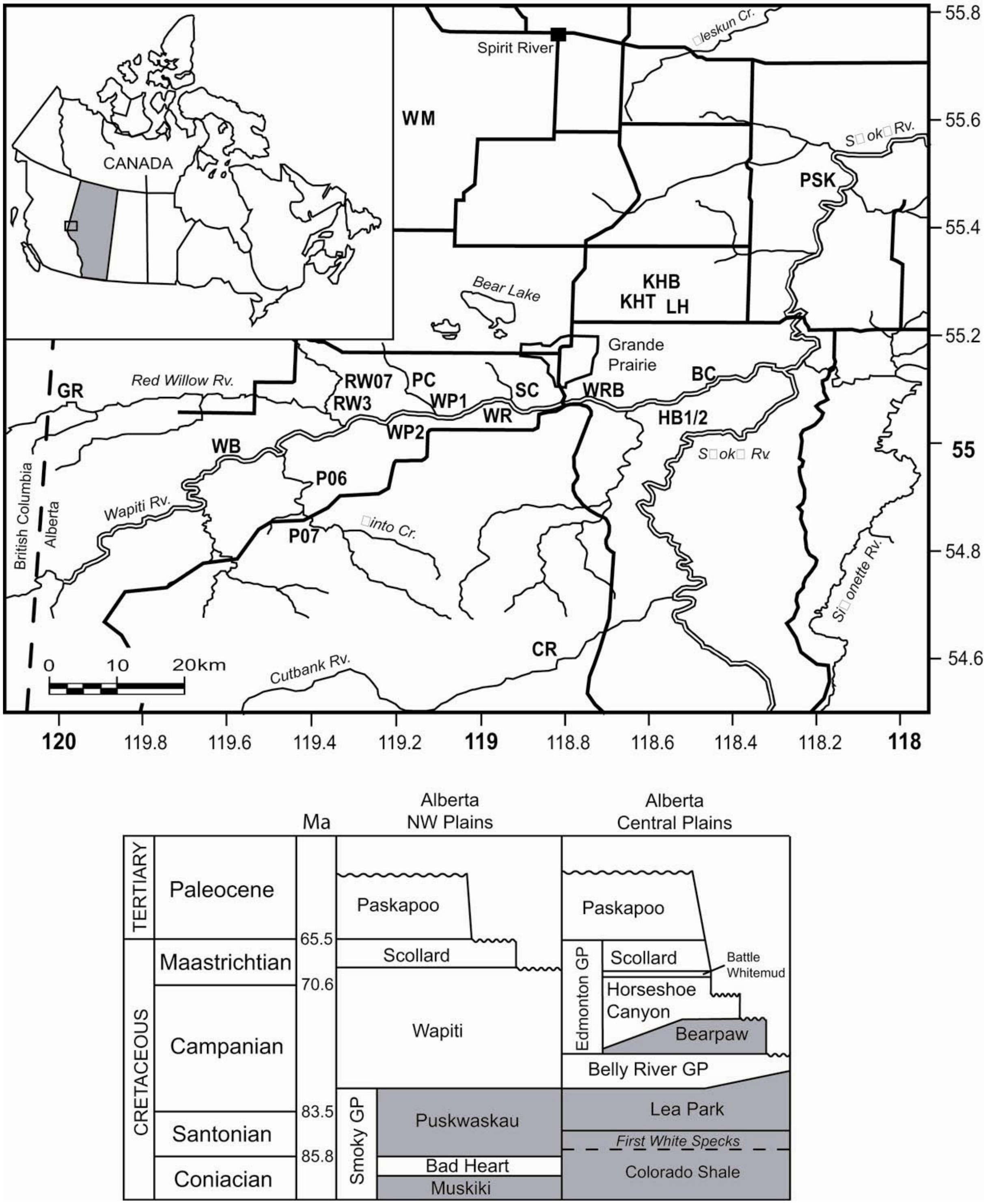
	PSK	WM	BC	HB1	HB2	KHB	LH	KHT	WRB	SC	WP1	WP2	PC	WR	RW07	RW3	GR	WB	P06	P07	CUT
Oxides (wt%)																					
SiO_2	47,20	60,25	57,05	67,23	53,32	62,35	66,32	58,07	62,99	56,26	66,58	68,67	58,46	72,34	56,83	57,51	53,84	56,00	51,53	57,55	53,81
TiO_2	0,30	0,72	0,17	0,52	0,15	0,23	0,57	0,29	0,62	0,35	0,70	0,16	0,18	0,73	0,18	0,21	0,18	0,18	0,26	0,53	0,16
Al_2O_3	17,49	15,04	19,25	13,99	17,59	15,53	14,52	19,33	17,43	20,47	15,78	15,25	20,61	13,43	21,88	21,54	19,18	20,47	25,63	17,03	18,88
Fe_2O_3	4,59	7,54	5,92	5,10	7,66	5,42	4,46	4,82	3,72	5,80	3,70	2,60	4,42	3,15	5,49	4,25	5,18	5,41	3,45	3,88	3,76
MnO	0,07	0,60	0,06	0,06	0,14	0,06	0,09	0,05	0,06	0,06	0,06	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
MgO	4,35	2,56	2,32	1,35	2,74	2,19	1,64	2,12	2,03	2,12	1,17	1,59	1,94	0,82	1,90	2,33	2,97	2,54	2,23	2,99	3,51
CaO	1,73	1,41	1,86	0,87	4,04	1,62	1,39	1,85	1,95	1,51	0,72	1,25	1,46	0,59	1,26	1,29	2,04	1,39	1,17	2,77	2,26
Na_2O	0,48	1,13	2,05	1,82	2,70	2,13	1,96	1,92	1,84	2,31	1,73	2,08	2,64	1,79	2,23	2,34	0,50	2,27	0,51	0,46	0,30
K_2O	0,38	1,56	0,64	1,41	0,80	0,64	1,67	1,04	1,37	1,34	2,42	0,77	0,96	2,20	1,09	1,10	0,77	0,77	3,08	0,30	0,46
P_2O_5	0,09	0,11	0,07	0,02	0,06	0,07	0,06	0,05	0,05	0,01	0,04	0,06	0,04	0,04	0,06	0,05	0,02	0,02	0,03	0,11	0,02
LOI	23,33	9,62	10,61	7,62	10,80	9,76	7,32	10,45	7,93	9,76	7,10	7,51	9,24	4,85	9,03	9,33	15,26	10,90	12,06	14,35	16,80
Tot.	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Trace elements (ppm)																					
Ba	110,6	1052,7	937,2	856,9	979,3	456,1	890,7	628,0	1258,4	702,1	673,6	2280,2	1140,9	596,7	610,1	238,9	142,6	1042,9	2184,3	342,5	212,6
Ce	132,1	19,8	82,7	53,6	88,2	75,1	63,9	99,8	69,2	76,1	44,6	32,5	140,5	34,7	68,4	88,2	91,8	100,1	105,7	67,5	64,7
Co	10,6	13,8	3,00	7,30	10,0	5,80	7,0	6,6	<3	5,20	12,4	<3	<3	3,30	5,90	<3	4,10	7,00	4,00	<3	<3
Cr	<3	64,8	10,9	59,1	<3	11,0	53,4	27,4	55,1	15,4	72,0	11,9	<3	76,6	<3	3,00	<3	<3	21,7	11,8	<3
Cu	18,7	37,8	5,40	15,9	13,1	7,7	23,5	8,9	20,6	10,9	26,7	9,90	7,10	16,2	6,60	<3	10,9	6,20	8,40	9,60	3,90
La	43,6	21,9	24,9	21,2	40,1	33,2	22,4	45,2	28,6	26,6	22,5	28,7	48,6	15,3	26,9	34,6	29,9	37,0	38,7	26,6	35,2
Nb	13,6	9,2	20,1	7,40	34,9	18,9	19,5	22,2	7,10	15,4	15,8	16,9	31,5	15,2	15,5	18,3	14,8	18,6	21,8	16,1	11,4
Ni	34,6	50	17,2	23,0	15,3	16,8	31,5	28,3	21,6	19,9	59,4	10,8	8,80	19,9	13,1	15,6	8,60	21,2	19,0	11,5	4,0
Pb	21,4	1854,7	49,1	10,5	41,2	22,8	13,0	41,1	<3	46,0	8,70	29,8	49,2	22,2	54,0	61,9	39,7	50,0	41,4	24,7	31,9
Rb	<3	64,2	20,7	33,1	19,3	12,8	83,4	27,4	<3	46,1	127,9	9,40	23,0	83,5	31,3	33,6	20,0	21,6	80,1	8,00	15,5
S	15130	215,6	1150	1140	620	180	1161,8	490	<3	560	<3	<3	670	1110	800	950	800	<3	730	1290	<3
Sc	<3	4,2	<3	13,7	5,80	<3	9,4	<3	12,30	5,30	12,6	4,30	3,90	11,3	3,40	<3	7,70	8,40	10,3	<3	<3
Sr	252,2	185,6	498,7	73,2	425,4	206,3	257,0	242,7	<3	401,5	209,3	394,0	660,9	165,4	410,3	421,2	209,7	374,5	217,3	317,9	191,9
Th	15,2	7,8	38,5	7,80	53,6	32,5	12,1	29,7	<3	35,8	18,3	17,8	28,0	3,50	32,2	28,8	30,1	33,1	32,8	26,5	28,7
V	24,7	127,5	14,1	91,6	7,60	23,8	90,7	28,0	86,2	30,4	124,1	17,3	9,30	86,8	12,3	14,9	11,9	16,9	47,8	30,9	7,6
Y	45,6	24	25,9	11,7	41,6	24,8	22,6	43,9	13,4	27,8	21,0	19,3	38,7	21,8	25,5	26,9	28,9	34,4	45,7	15,0	9,5
Zn	104,2	89,9	76,9	63,0	67,3	61,7	81,7	110,6	94,2	75,7	65,3	68,0	129,3	32,5	118,1	68,2	75,6	108,3	184,0	64,1	41,2
Zr	195,1	124,9	154,9	29,4	125,2	120,6	170,1	288,8	<3	158,9	142,7	111,9	275,8	202,8	177,0	178,6	230,4	243,7	270,4	268,3	100,6

Table 2

	Pre-Bearpaw	Bearpaw	Post-Bearpaw
	Age >74 MY	74<Age<73	Age<73
TAS			
Basalt	1	0	0
Basaltic andesite	3	1	2
Andesite	9	4	6
Dacite	2	7	11
Rhyolite	0	2	1
N° Samples	15	14	20

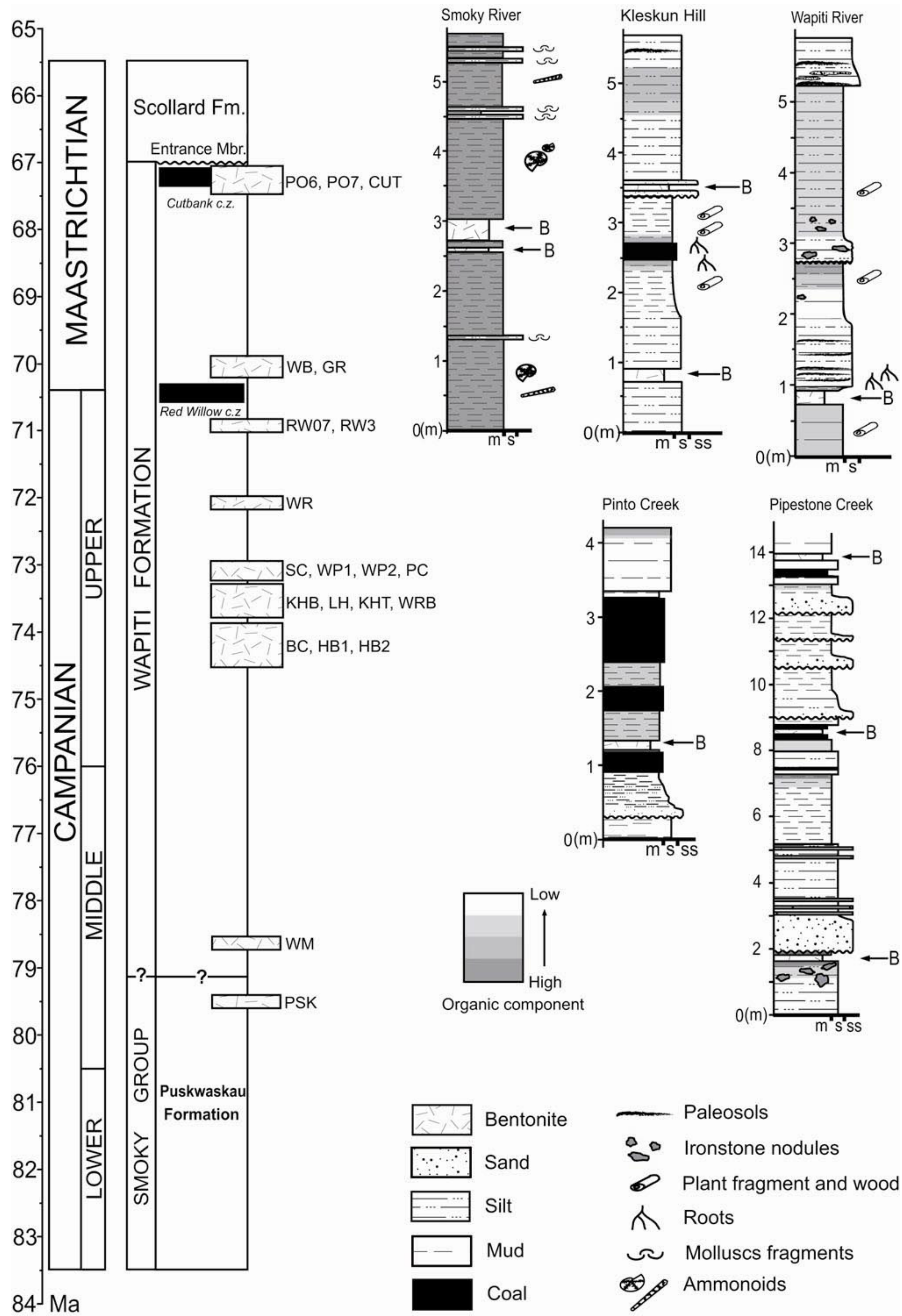
	Geographic Area					
	Montana	Southern Alberta	Central Alberta	NW Alberta	Grande Prairie	Manitoba
TAS						
Basalt	0	0	1	0	0	0
Basaltic andesite	0	1	5	0	0	2
Andesite	3	3	3	3	8	0
Dacite	1	1	1	5	11	0
Rhyolite	0	0	1	0	2	0
N° Samples	4	5	11	8	21	2

Table 3



55.8
55.6
55.4
55.2
55
54.8
54.6
120
119.8
119.6
119.4
119.2
119
118.8
118.6
118.4
118.2
118
CANADA
Spirit River
WM
PSK
KHB
KHT
LH
Bear Lake
Grande Prairie
GR
Red Willow Rv.
RW07
RW3
PC
WP1
SC
WRB
BC
WR
WP2
HB1/2
WB
P06
P07
Wapiti Rv.
British Columbia
Alberta
CR
Cutbank Rv.
0 10 20km
Ma
Alberta NW Plains
Alberta Central Plains
TERTIARY
Paleocene
CRETACEOUS
Maastrichtian
Campanian
Santonian
Coniacian
65.5
70.6
83.5
85.8
Paskapoo
Scollard
Wapiti
Smoky GP
Puskwaskau
Bad Heart
Muskiki
Edmonton GP
Horseshoe Canyon
Battle
Whitemud
Bearpaw
Belly River GP
Lea Park
First White Specks
Colorado Shale

Figure 1



Smoky River
Kleskun Hill
Wapiti River
Pinto Creek
Pipestone Creek
MAASTRICHTIAN
CAMPANIAN
UPPER
MIDDLE
LOWER
Scollard Fm.
Entrance Mbr.
Cutbank c.z.
Red Willow c.z
WAPITI FORMATION
SMOKY GROUP
Puskwaskau Formation
PO6, PO7, CUT
WB, GR
RW07, RW3
WR
SC, WP1, WP2, PC
KHB, LH, KHT, WRB
BC, HB1, HB2
WM
PSK
Ma
Low
High
Organic component
Bentonite
Sand
Silt
Mud
Coal
Paleosols
Ironstone nodules
Plant fragment and wood
Roots
Molluscs fragments
Ammonoids

Figure 2

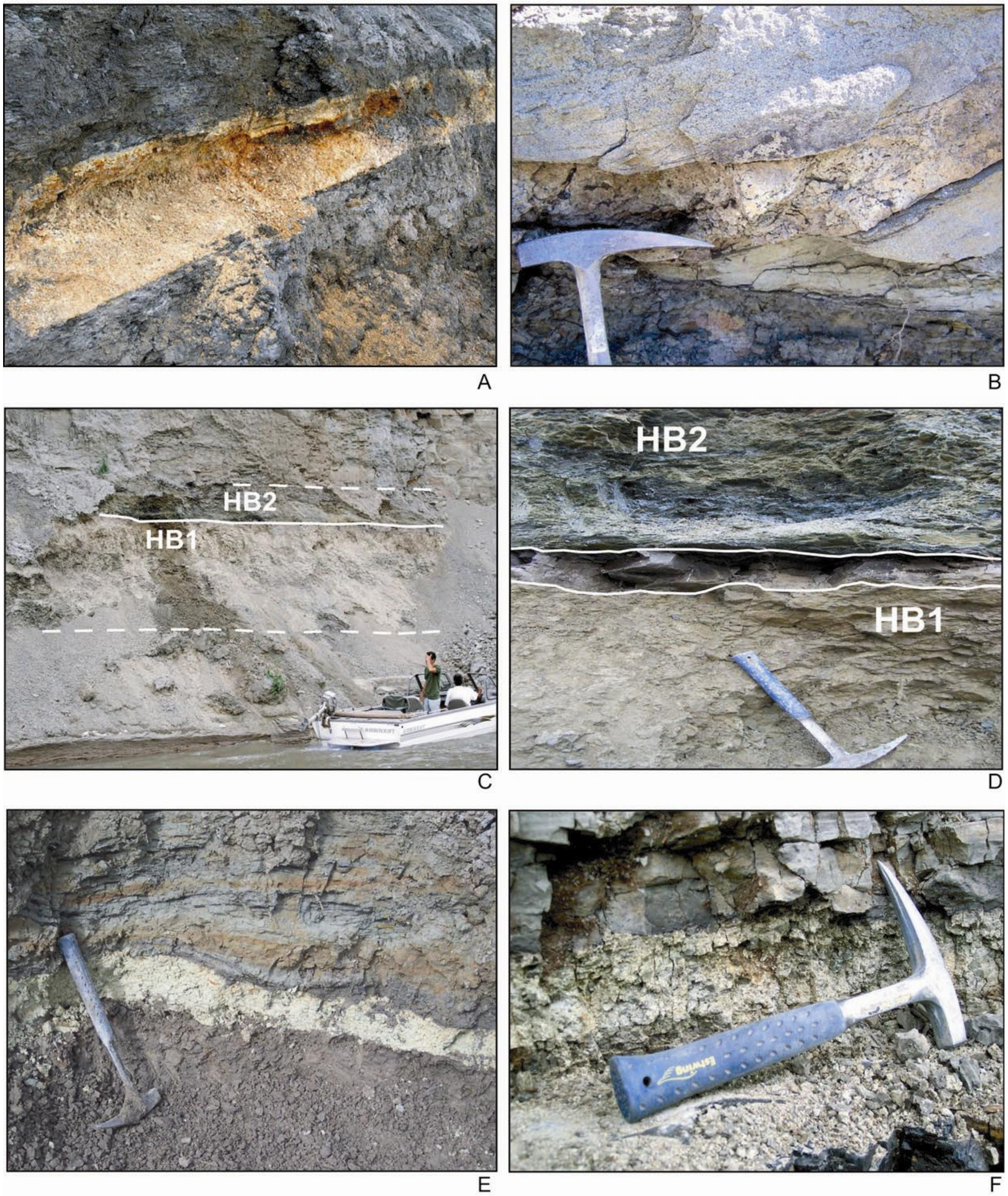


Figure 3

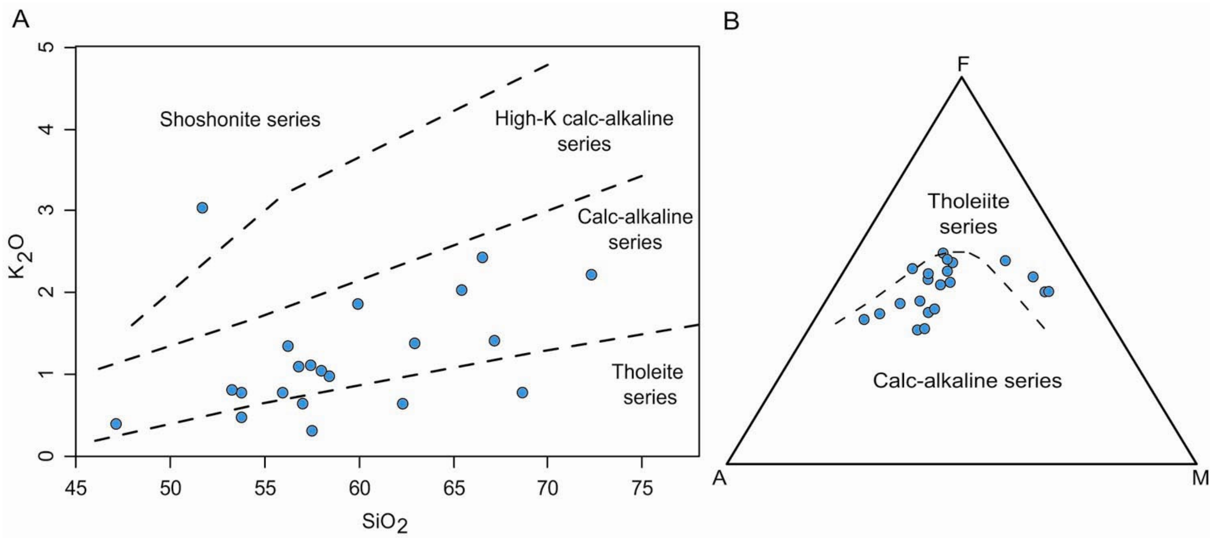
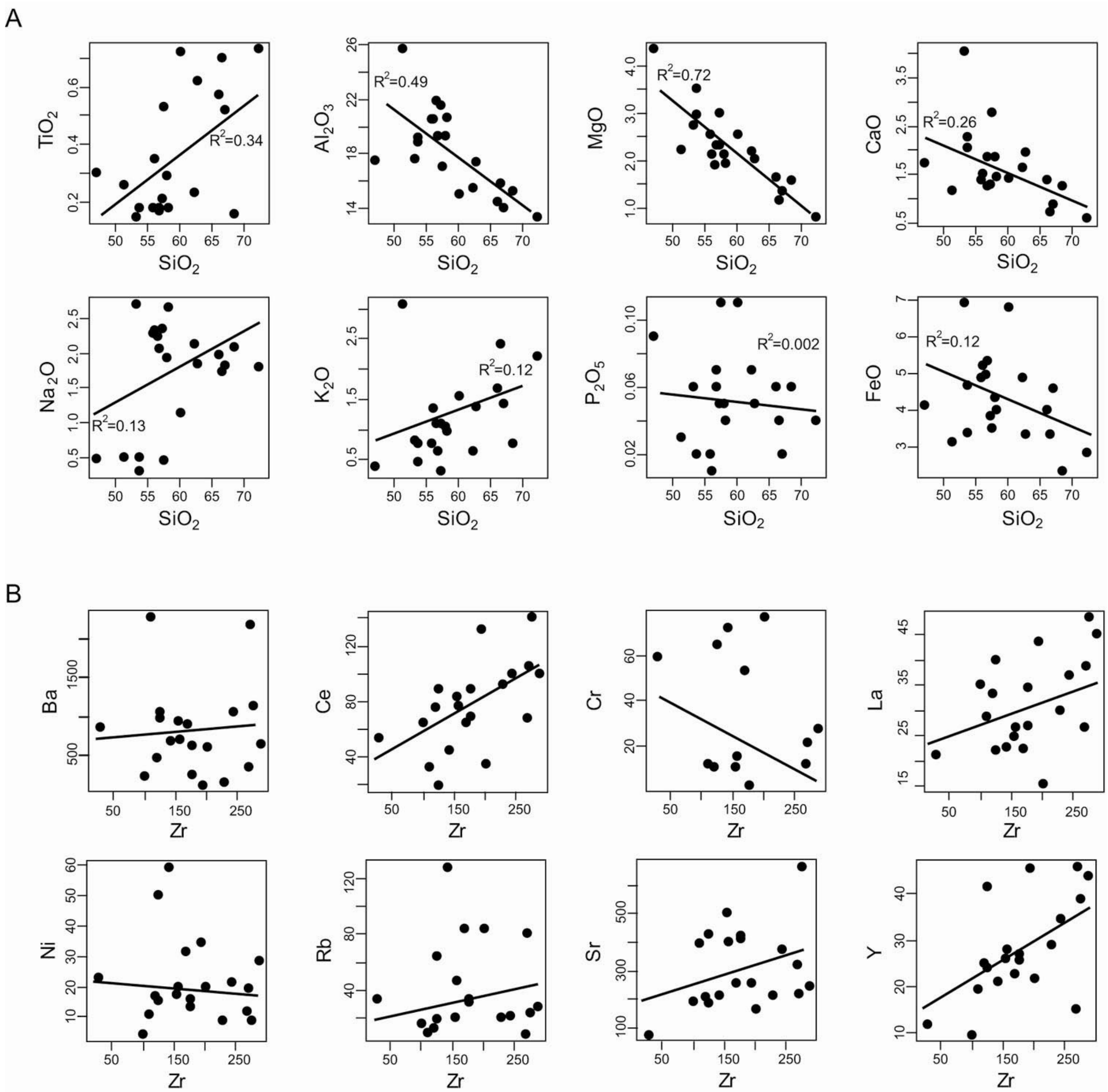
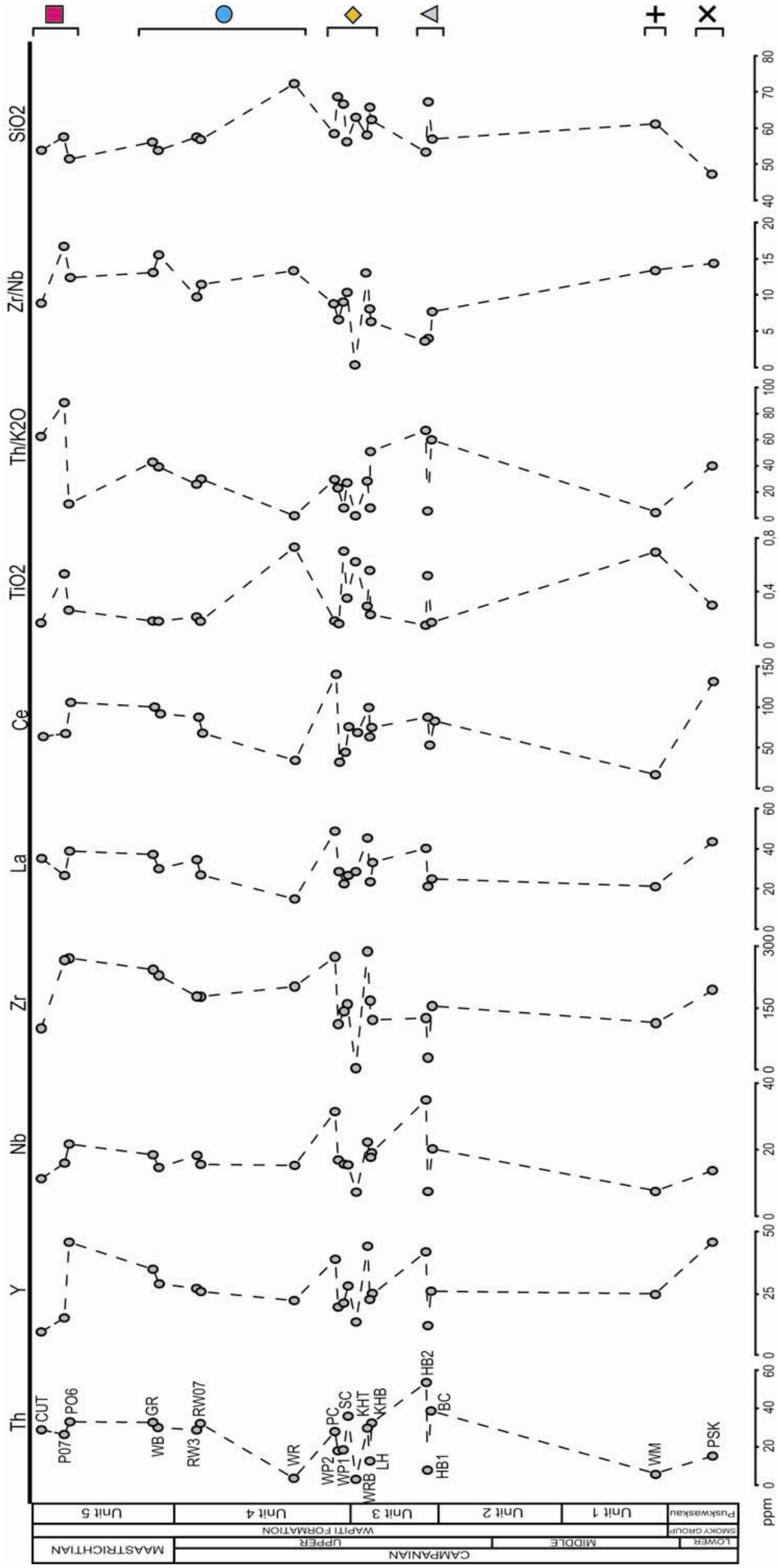

A
Shoshonite series
High-K calc-alkaline series
Calc-alkaline series
Tholeite series
K_2O
SiO_2
B
F
Tholeiite series
Calc-alkaline series
A
M

Figure 4



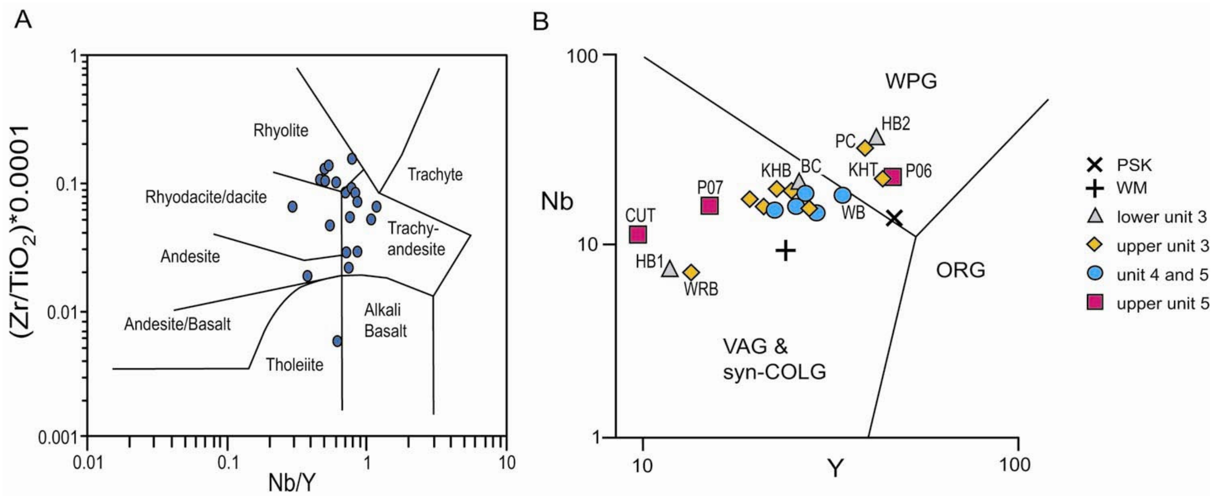
A
TiO2
SiO2
R²=0.34
Al2O3
R²=0.49
MgO
R²=0.72
CaO
R²=0.26
Na2O
R²=0.13
K2O
R²=0.12
P2O5
R²=0.002
FeO
R²=0.12
B
Ba
Zr
Ce
Cr
La
Ni
Rb
Sr
Y

Figure 5



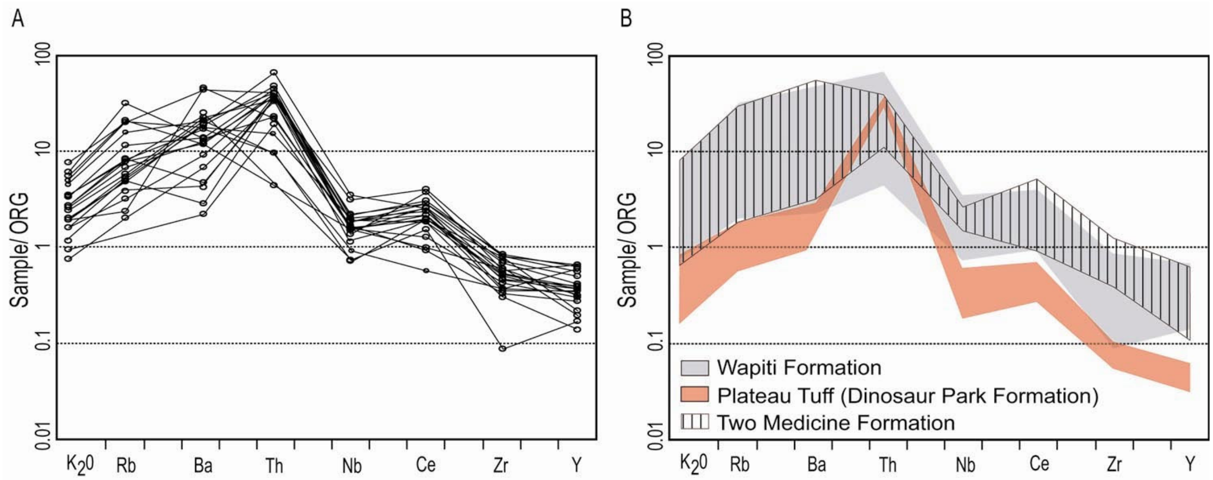
Th
Y
Nb
Zr
La
Ce
TiO2
Th/K2O
Zr/Nb
SiO2
ppm
CUT
P07
PO6
WB
GR
RW3
RW07
WR
WP2
WP1
PC
SC
WRB
KHT
KHB
LH
HB1
HB2
BC
WM
PSK
Unit 5
Unit 4
Unit 3
Unit 2
Unit 1
Puskwaskau
WAPITI FORMATION
SMOKY GROUP
UPPER
MIDDLE
LOWER
MAASTRICHTIAN
CAMPANIAN

Figure 6



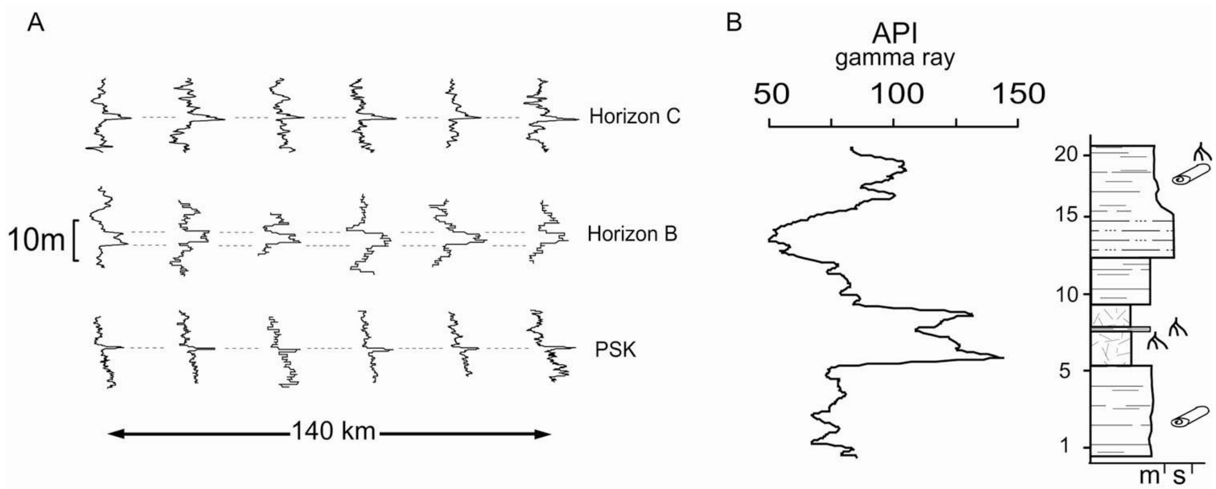
A
(Zr/TiO2)*0.0001
Nb/Y
Rhyolite
Trachyte
Rhyodacite/dacite
Trachy-
andesite
Andesite
Andesite/Basalt
Alkali
Basalt
Tholeiite
B
Nb
Y
WPG
ORG
VAG &
syn-COLG
HB2
PC
KHB
BC
KHT
P06
P07
CUT
WB
HB1
WRB
PSK
WM
lower unit 3
upper unit 3
unit 4 and 5
upper unit 5

Figure 7



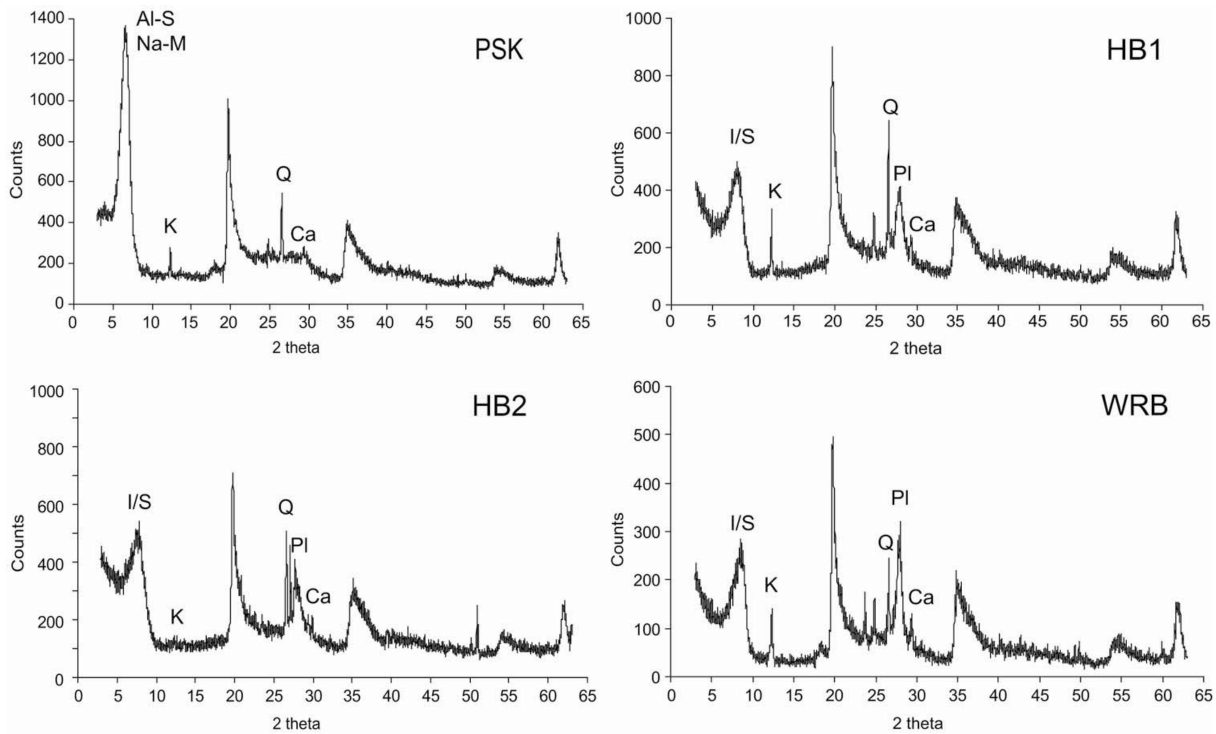
A
B
Sample/ORG
100
10
1
0.1
0.01
K2O
Rb
Ba
Th
Nb
Ce
Zr
Y
Wapiti Formation
Plateau Tuff (Dinosaur Park Formation)
Two Medicine Formation

Figure 8



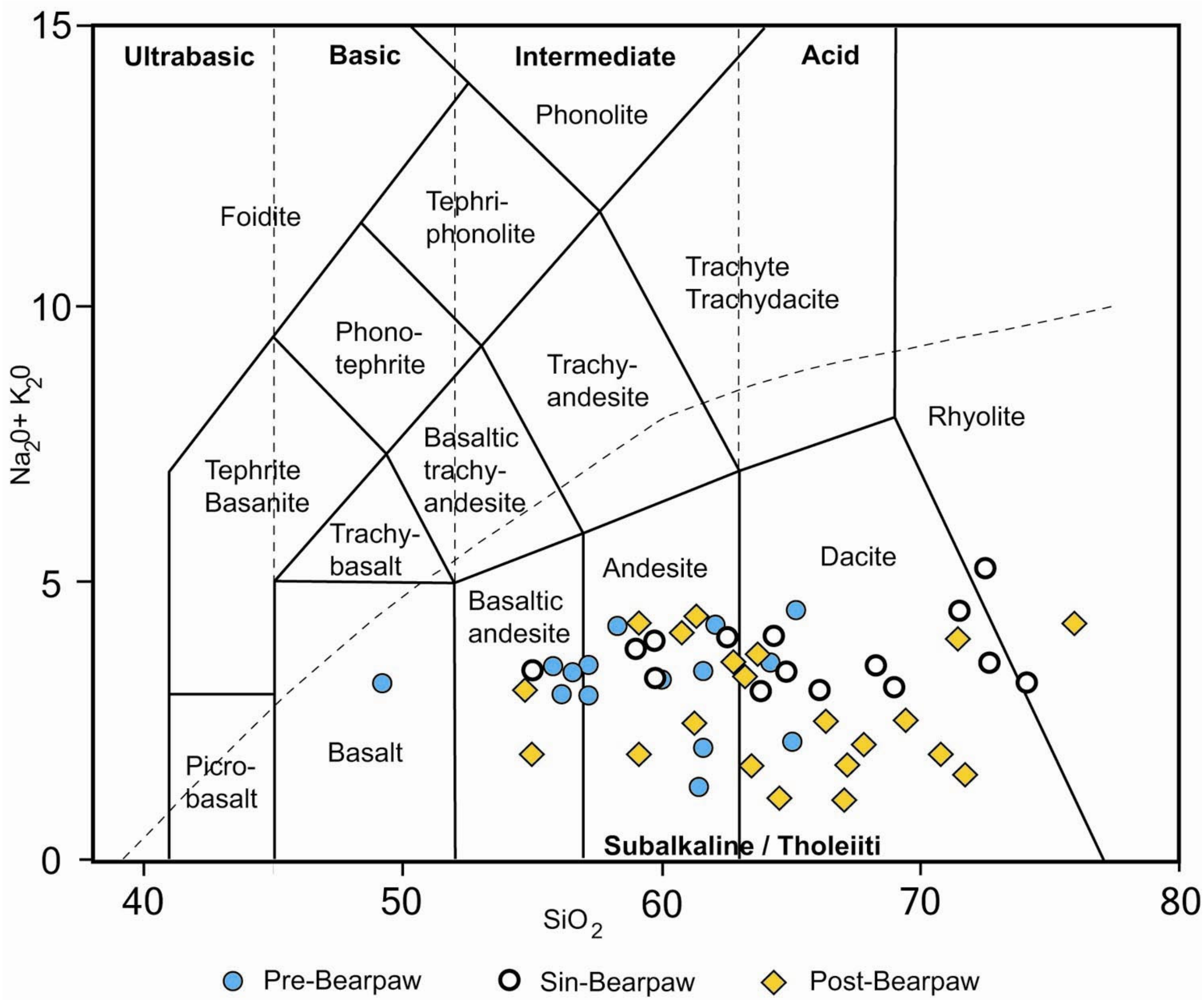
A
Horizon C
10m
Horizon B
PSK
140 km
B
API
gamma ray
50
100
150
20
15
10
5
1
m
s

Figure 9



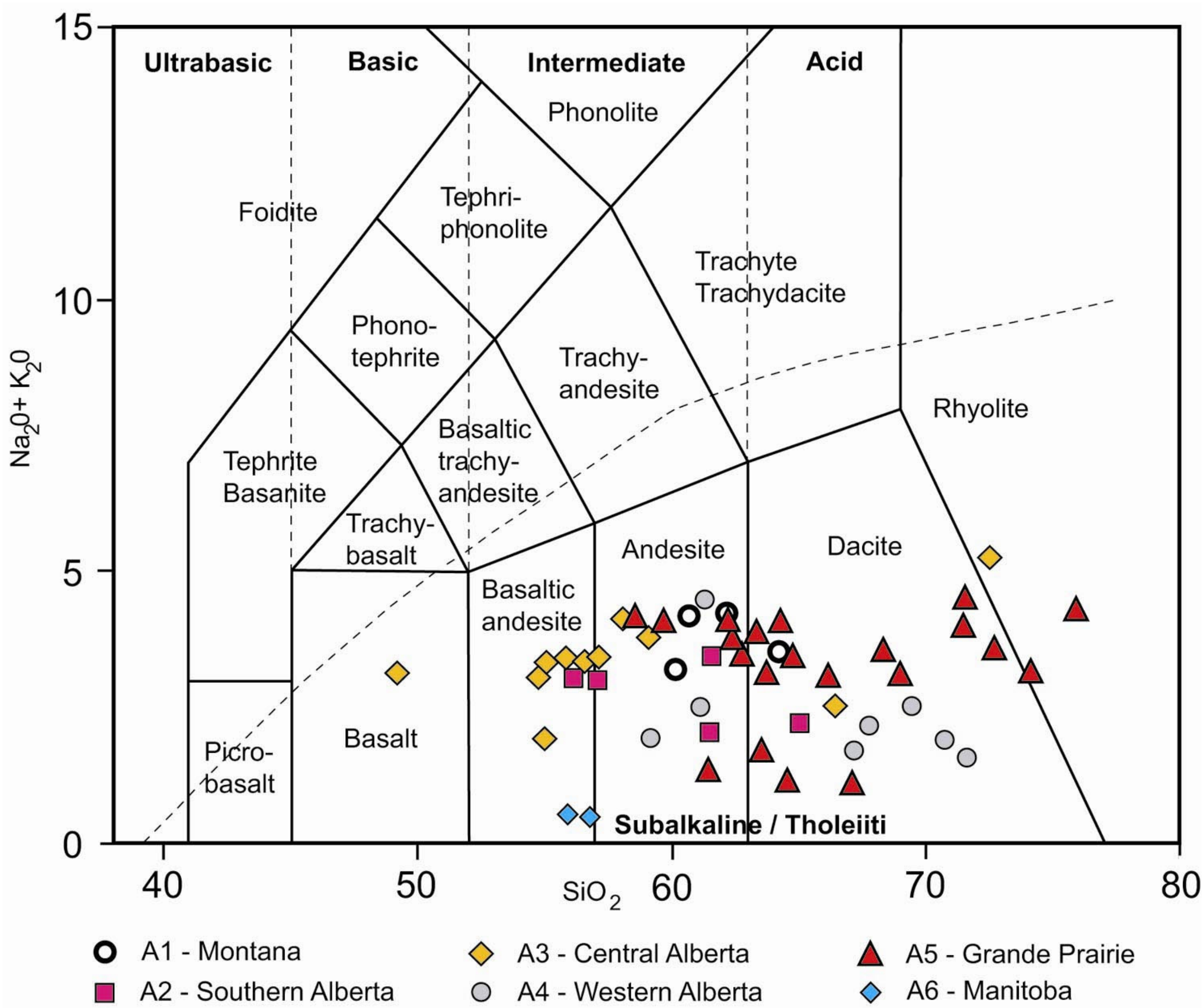
PSK
Al-S
Na-M
K
Q
Ca
Counts
2 theta
HB1
I/S
K
Q
Pl
Ca
Counts
2 theta
HB2
I/S
K
Q
Pl
Ca
Counts
2 theta
WRB
I/S
K
Q
Pl
Ca
Counts
2 theta

Figure 10



15
10
5
0
Ultrabasic
Basic
Intermediate
Acid
Phonolite
Foidite
Tephri-
phonolite
Trachyte
Trachydacite
Phono-
tephrite
Trachy-
andesite
Rhyolite
Tephrite
Basanite
Basaltic
trachy-
andesite
Trachy-
basalt
Andesite
Dacite
Basaltic
andesite
Basalt
Picro-
basalt
Subalkaline / Tholeiiti
$Na_20+ K_20$
40
50
60
70
80
SiO_2
Pre-Bearpaw
Sin-Bearpaw
Post-Bearpaw

Figure 11



Ultrabasic
Basic
Intermediate
Acid
Phonolite
Foidite
Tephri-phonolite
Trachyte Trachydacite
Phono-tephrite
Trachy-andesite
Rhyolite
Tephrite Basanite
Basaltic trachy-andesite
Trachy-basalt
Andesite
Dacite
Basaltic andesite
Picro-basalt
Basalt
Subalkaline / Tholeiiti
Na_20+K_20
SiO_2
15
10
5
0
40
50
60
70
80
A1 - Montana
A2 - Southern Alberta
A3 - Central Alberta
A4 - Western Alberta
A5 - Grande Prairie
A6 - Manitoba

Figure 12

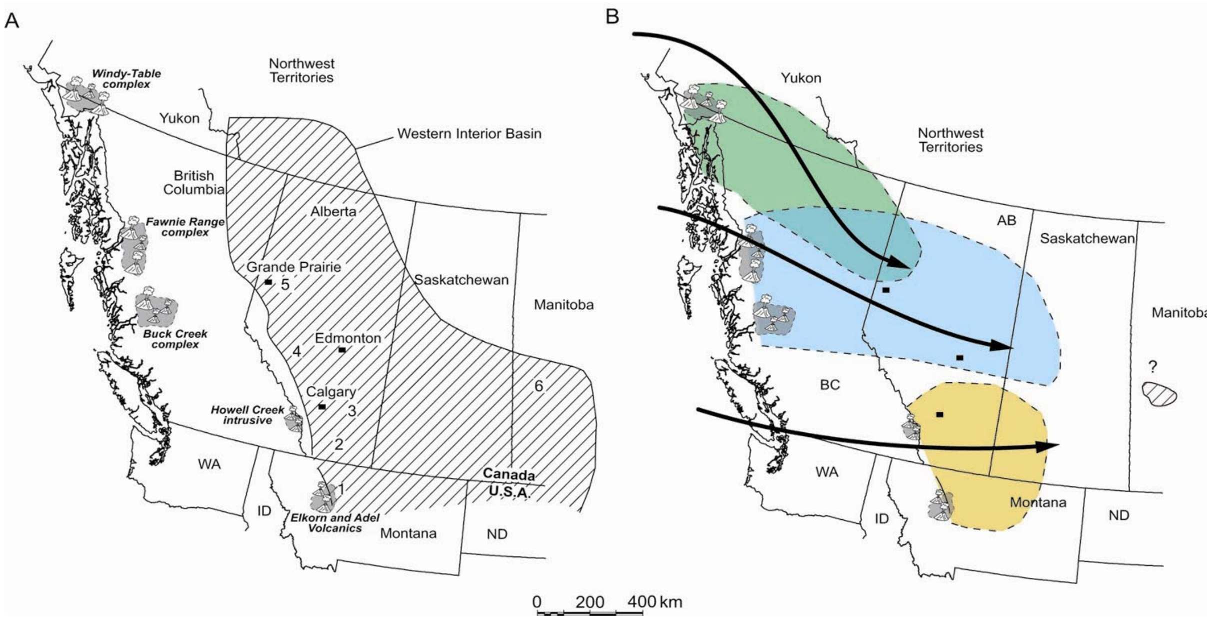

A
Windy-Table complex
Northwest Territories
Yukon
Western Interior Basin
British Columbia
Fawnie Range complex
Alberta
Grande Prairie
5
Saskatchewan
Manitoba
Buck Creek complex
Edmonton
4
Calgary
3
2
6
Howell Creek intrusive
WA
ID
1
Elkorn and Adel Volcanics
Montana
ND
Canada
U.S.A.
0 200 400 km
B
Yukon
Northwest Territories
AB
Saskatchewan
Manitoba
BC
?
WA
ID
Montana
ND

Figure 13

Paper 3

FLUVIAL SEQUENCE STRATIGRAPHY: THE WAPITI FORMATION, WEST-CENTRAL ALBERTA, CANADA.

Authors

FEDERICO FANTI

Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Università di Bologna, Via Zamboni 67, 40126 Bologna, Italy

Corresponding author: Tel: +39 051 2094565; Fax: +39 051 2094522;

Email: federico.fanti@unibo.it

OCTAVIAN CATUNEANU

University of Alberta, Department of Earth and Atmospheric Sciences

Tel: +1 780 492 6569; Fax: +1 780 492 7598

1-26 Earth Sciences Building, Edmonton, Alberta, Canada T6G 2E3

Email: octavian@ualberta.ca

ABSTRACT

Excellent outcrop exposures and high-resolution subcrop data allow the description and confident tracing of four stratigraphic discontinuities in the fully non-marine strata of the Campanian-Maastrichtian Wapiti Formation (Western Interior foreland basin, Alberta, Canada). The framework identifies four unconformity-bounded depositional sequences (A-D), based on sequence stratigraphic methodology, well-log patterns, facies analysis, and fossil associations. In ascending order, sequence A records the transition from the underlying marine facies of the Puskwaskau Formation into the Wapiti fluvial facies, and consists of strongly progradational and aggradational stacking patterns. Sequences B and C show a similar pattern of basal amalgamated channel-fill deposits that grade upwards into floodplain-dominated strata. Finally, sequence D is dominated by channelized sediments and extensive overbank facies. An aggradational stacking patterns suggest deposition under high accommodation. Maximum flooding surfaces are interpreted within fine graded deposits in the upper portions of sequence C and D. They are tied to regionally extensive coals that accumulated more than 200 km away from the coeval shoreline. Stratigraphic discontinuities described in this report effectively subdivide non-marine strata of the Wapiti Formation in regionally mappable, tectonically controlled depositional sequences as well as genetic units that reflect major changes in relative base level. These thoroughgoing subaerial unconformities delimit alluvial successions that accumulated under both *upstream* and *downstream* controls on accommodation. The construction of a high-resolution stratigraphic framework in the fully non-marine facies of the Wapiti Formation enables the analysis of fluvial architecture and depositional processes within the evolving context of the Late Cretaceous Alberta foreland basin.

Key words: Fluvial sequence stratigraphy, Wapiti Formation, coal seams, maximum flooding surface, subaerial unconformities.

1. INTRODUCTION

The application of the concepts of sequence stratigraphy to non-marine successions is one of the more controversial and less documented topics in current stratigraphic research. Since the relationships between fluvial beds in the proximal section of a sedimentary basin and correlative paralic deposits are often unclear, widely accepted sequence stratigraphic models are applied with particular care in strictly alluvial successions. Nevertheless, after the development of the initial sequence stratigraphic models (Posamentier and Vail, 1988; Miall, 1991; Schumm, 1993; Marriott, 1999; Posamentier and Allen, 1999), in recent years several works have dealt with the applicability of such approaches to the alluvial setting on the basis of both theoretical and empirical approaches (Wood et al., 1993; Shanley and McCabe, 1998; Posamentier, 2001; Catuneanu et al., 2003; Catuneanu, 2006). Among the most frequently discussed topics are (1) the competing effects of major controlling factors (i.e., tectonism, base-level oscillation, and climate) in the different portions of the basin, and (2) the identification and correlation of time significant sequence stratigraphic surfaces. Although unconformity-bounded units have long been recognized in non-marine strata, sequence stratigraphic principles have been applied across a limited geographic extent (Eberth and Hamblin, 1993; Schumm, 1993; Shanley and McCabe, 1994; Hamblin and Abrahamson, 1996; Hamblin, 1997a, b; Rogers, 1998; Catuneanu and Sweet, 1999; Catuneanu and Sweet, 1999; Miall and Arush, 2001).

The Late Cretaceous deposits of the Wapiti Formation (west-central Alberta, Canada) represent an ideal study case to investigate how concepts of sequence stratigraphy may be applied to non-marine successions. The Wapiti wedge represents approximately 15 My (from the middle Campanian to the early Maastrichtian) of strictly alluvial deposition in the proximal section of the Albertan segment of the Western Interior Basin (WIB). Sediments originated in the rising Canadian Cordillera to the west, whereas the deposition in the eastern margin was influenced by second-order (and shorter 3rd to 5th-order) transgressive-regressive cycles. Thrusting, lithospheric loading and load-induced foreland subsidence resulted in the accumulation of a thick clastic prism that reaches a thickness of 1300 meters at its western edge. Different stages of regional uplift (or rebound) and increase in subsidence resulted in the formation of regional unconformable boundaries between sequences preserved in the Wapiti and equivalent formations.

2. STUDY AREA

The Wapiti Formation crops out extensively in west-central Alberta (Fig. 1), covering more than 75,000 square kilometres between latitudes 53° and 57°N, and longitudes 112° and 121°W, from the Edmonton region in the south (central Alberta) to Tumbler Ridge in the northwest (British

Columbia). In the Smoky River area and farther west in British Columbia the Wapiti succession is entirely exposed along major and minor river valleys. A dense subsurface database related to oil and gas exploration exists and provides a robust framework for stratigraphic analysis. Data presented in this study refer primarily to the Grande Prairie area, between latitude 54° and 55°N, and longitude 118° and 121°W. In addition, subsurface data were collected from the foothill region between Grande Prairie and Red Deer (lat. 52°N, long. 113°W) in order to document the lateral continuity of discussed sequences.

2.1. Geology and stratigraphy

The Wapiti Formation consists of interbedded fluvial sandstone, siltstone, and mudstone, with subordinate coal and lacustrine sediments that form an eastward-thinning wedge. A recent stratigraphic revision of the Wapiti Formation in the Grande Prairie region resulted in the identification of five lithostratigraphic units, whose study and description have been based on well-log signatures, lithofacies analysis, sedimentology, petrography, palynology, and fossil association (Fanti and Catuneanu, in prep.). Newly defined units consist primarily of fining-upward sequences bounded by subaerial unconformities of undetermined duration. In addition, discrete coal horizons – Basal, unit 3, Red Willow, and Cutbank coal zones – contain extensive tabular coals that represent a powerful tool for regional correlations. The stratigraphic interval studied in this paper is equivalent to the entire Belly River to Battle succession of central and southern Alberta (Eberth, 1990, 2002, 2005; Eberth and Hamblin, 1992; Dawson et al., 1994a, b; Brinkman et al., 1998; Catuneanu et al., 2000), and to the Brazeau and lower Coalspur formations south and west of the Alberta Syncline (Rahmani and Lerbekmo, 1975; Dawson at al., 1989, Osborn et al., 2006).

In the central and southern section of the basin, the marine Bearpaw Formation marks the top and the base of the two major clastic wedges, the Belly River and Edmonton Groups. Differently, in the Wapiti Formation the Bearpaw shales are absent; furthermore, the lacustrine deposits of the Whitemud and Battle formations which cap the Edmonton Group in the Alberta plains are difficult do identify either in outcrop and well logs. The Entrance Member (help the reader find this on a figure 2) represents the upper boundary of the Wapiti Formation and is equivalent to the Entrance conglomerate of the central foothills as well as to resistant sand units at the base of the Scollard and Coalspur formations (Jerzykiewicz and McLean, 1980; Jerzykiewicz, 1985a, b; Mack and Jerzykiewicz, 1989; Dawson et al., 1994a).

The table of formations in Fig. 2 summarize currently proposed and accepted lithostratigraphic nomenclatures applied to Western Interior Basin deposits of Alberta and Montana for the Campanian-Maastrichtian interval.

2.2. Tectonic setting

The Wapiti Formation and coeval Belly River and Edmonton groups, unquestionably represent a phase of great sediment supply to the foreland basin. Recent studies on reciprocal sequence architecture of marine and non-marine Campanian to Paleocene successions of the Western Interior Basin indicate that the foreland basin stratigraphy is characterized by third-order cyclicity developed in response to opposite flexural tectonics between foredeep and forebulge settings separated by a hinge zone of facies transition (Eberth and Hambliln, 1993; Catuneanu et al., 1997; Catuneanu and Sweet, 1999; Catuneanu et al., 2000). Particularly, along-strike (i.e., northwest-southeast) diachroneity of orogenic processes along the Canadian Cordillera and remarkable differences in crustal shortening from the north to the south (in the order of 50 and 150 km respectively) determined different timing and amplitude of flexural subsidence and an overall south-eastward sediment transport (Cant and Stockmal, 1989; Eberth and Hamblin, 1993) (Fig. 3). Price (1994), indicate that the net basement subsidence ranges from 5-6 km in the southwest, to 2-3 km in the northeast, and to one fifth of that amount north of 56°N latitude. This latitude coincides with the northern section of the study area in the Grande Prairie region and also would roughly represent the hypothetical Late Cretaceous hinge line position in the area. In addition, the simultaneous orogenic pulse in the Cordillera and reactivation of the Peace River Arch in the Maastrichtian (Gleddie, 1949; Chen and Bergman, 1999) largely contributed to the south-eastward plunge of the Wapiti wedge along both sides of the Alberta Syncline (Fig. 4).

Overall, well known clastic successions of southern Alberta (i.e., Belly River and Edmonton groups) and their formations are defined by 3rd and 4th order sequences that record base level oscillations, tectonically induced changes in sediment supply and climatic variations (Bhattacharya and Posamentier, 1994; Catuneanu and Sweet, 1999; Catuneanu et al., 2000; Eberth, 2002). Furthermore, cryptic sequence boundaries within non-marine successions have been commonly identified, among the others, by major changes in depositional geometries, petrography, and lithostratigraphy (Eberth and Hamblin, 1993; Hamblin and Abrahamson, 1996; Hamblin 1997a, b; Chen and Bergman, 1999; Chen et al., 2005).

3. DATA AND METHODS

The data for this paper were primarily collected by means of detailed outcrop facies analyses of Wapiti beds coupled with dense well log coverage in the Grande Prairie area (west-central Alberta). Data from 640 exploration boreholes were used to assemble ten sections encompassing the stratigraphic interval from the uppermost Puskwaskau Formation through approximately 600 meters of the Wapiti Formation. Gamma ray curves provided the most accurate representation of lithology, sequence stratigraphic boundaries, and major marker layers. Sections were SW-NE dip-oriented and NW-SE strike-oriented and correlation was accomplished by pattern matching stratigraphic surfaces and marker beds (such as coal and bentonite beds). To support lateral correlation of Wapiti beds, cross-sections in the Grande Prairie area were tied to a single cross-section oriented along strike toward the Red Deer area, south of Edmonton, where the Bearpaw marine shales are well represented in both outcrop and subsurface. Well 07-27-068-11W6 (lat. 54° 91'; long. 119° 58') is the reference log used in this study to document the occurrence of stratigraphic unconformities and marker beds in the Grande Prairie area; wells 15-27-047-7W5 and 11-07-043-3W5 are reference log for the identification of the Oldman, Dinosaur Park, Bearpaw, and Horseshoe Canyon formations contacts in central Alberta (after Chen et al., 2005).

Detailed discussion of the lithostratigraphy, coal zones, and key stratigraphic surfaces (including subaerial unconformity and maximum flooding surfaces) are provided in Dawson et al., (1994a), Fanti (in prep.), and Fanti and Catuneanu (in prep.). Palynological assemblages are supplemented by published information from Srivastava (1970), Jerzykiewicz and Sweet (1988), Sweet et al. (1989), and Dawson et al. (1994a). Radioisotopic ages presented in stratigraphic charts are from Rogers et al. (1993), Eberth and Deino (2005), Eberth (2005), Fanti (2007), Mumpy and Catueanu (2007), and Currie et al. (2008).

The sequence stratigraphic interpretation of the clastic deposits of the Wapiti Formation is based on detailed description of facies associations as well as on the nature of the contacts that separate them. Sequence stratigraphic nomenclature and terminology adopted in this paper follows Galloway (1989), Catuneanu and Sweet (1999) and Catuneanu (2002, 2006).

3. SEQUENCE STRATIGRAPHIC BACKGROUND

It is widely held that that fluvial systems feel the influence of marine base-level changes only a limited distance upstream from the coeval shoreline. This distance varies according to different models and generally ranges between 30 and 300 km (Shanley et al., 1992; Schumm, 1993; Posamentier, 2001; Amorosi and Colalongo, 2005). Critical factors include overall alluvial plain gradient and tectonic context. Blum and Tornqvist (2000) extended this limit further upstream (up to 400 km upstream) by referring to the extent of coastal onlap during trangressive events for low-gradient landscapes. The landward limit of base-level control on fluvial behaviour separates two distinct domains in the basin: one dominated by *upstream* controls and the other dominated by *downstream* controls (Catuneanu, 2006). The importance of distinguishing these domains within the foreland basin is of paramount importance: where fluvial processes of aggradation and incision are unaffected by base level shifts, low- and high-accommodation systems tract (or succession) terminology is preferred to lowstand – transgresssive – highstand systems tract (Olsen et al., 1995; Dahle et al., 1997; Catuneanu and Sweet, 1999; Catuneanu and Elango, 2001). Moreover, Wapiti stratigraphic architecture and distribution of major sequence boundaries indicate that both *upstream* and *downstream* controls alternatively influenced the alluvial deposition .

In addition, regionally extensive coals that accumulate within alluvial setting exhibits all the characteristics essential to a sequence boundary (sensu Galloway, 1989): (1) they are lithologically distinctive and can be traced or correlate locally and regionally (primarily by their geochemical and lithotipic profile); (2) they have a time significance, recording isochronous emplacement of similar depositional setting and are also potentially datable; and (3), coal beds document gaps in the supply and deposition of clastic sediments. In addition, peat and coal accumulation and preservation can only occur under maintenance of water table at adequate levels and substantial vegetation cover, parameters that are both directly controlled by climatic variations. Consequently, following Hamilton and Tadros (1994), such deposits may indicate non-marine correlatives of marine maximum flooding surfaces, and consequently can be referred as sequence boundaries (*sensu* Galloway, 1989). Relationships between flooding surfaces and the development of coals, as well as the potential of regionally extensive coal beds in intrabasinal correlation are largely documented in the literature in both proximal and distal section of fluvial systems (Flores, 1984; Nurkowski and Rahmani, 1984; Jervey, 1988; Posamentier and Vail, 1988; Posamentier et al., 1988; Shanley et al., 1992; Bustin and Smith, 1993; Tibert and Gibling, 1999; Wadsworth et al., 2002; Zdravkov et al., 2006). With respect to more proximal sections of the alluvial plain, major raising of base level would concomitantly elevate the groundwater table producing more poorly drained conditions, with the development of wet soils, swamp, marshes, and lacustrine environments (Tye and Kosters, 1986; Shanley and McCabe, 1994).

4. SUBAERIAL UNCONFORMITIES IN THE WAPITI FORMATION

Non-marine sequence boundaries associated with subaerial unconformities are typically placed at the base of extensive, amalgamated fluvial-channel bodies which record prolonged deposition under low accommodation and sediment bypass. Their lateral expression can be represented by correlative mature paleosols or by the occurrence of maximum amalgamation of fluvial sand sheet (Posamentier and Allen, 1993; Olsen et al., 1995; Catuneanu, 2002, 2006). Such surfaces are also associated with undetermined time gaps and frequently mark abrupt basinward shifts of facies.

This study documents four subaerial unconformities (SU) in the Wapiti Formation using outcrop and well logs. The origin of the unconformities is associated with tectonically induced factors, particularly episodes of isostatic uplift during orogenic quiescence stages. In ascending order, upper contacts of unit 1, 2, 3, and 5 (*sensu* Fanti and Catuneanu, in prep.) represent mappable subaerial unconformities recording a gap in the stratigraphic record. Such interruptions in the continuity of depositional sequences serve in this study as depositional sequence boundaries

4.1. Transition between unit 1 and 2 – SU1.

The lower unconformity observed within the Wapiti succession marks the transition from unit 1 and unit 2, and occurs at approximately 120 meter above the base of the Wapiti Formation (Fig. 5). This sharp and strongly erosive contact juxtaposes fine-grained, coastal plain deposits of unit 1 and coarse, alluvial sandstones of unit 2 (Fig. 6B). Deposits of unit 1 reflect medium to high accommodation conditions, and include organic-rich mudstones and paleosols, widespread tabular coal seams, and relatively thin (< 1.5 meters) channel sandstones. In contrast, overlying beds of unit 2 consists of fining upward channel sandstones up to 30 meter thick and include a variety of interbedded finer deposits that represent channel top, channel margin and levee, and overbank paleoenvironments. Coal beds are rare and discontinuous, usually associated to wet and immature paleosols. This contact is easily recognized in well log by a blocky, low gamma response and is also associated with an increase in matrix porosity Best exposures of this unconformity are located along the Smoky and Simonette Rivers, east of Grande Prairie.

4.2. Transition between unit 2 and 3 – SU2.

This erosive-based unit boundary occurs at approximately 220 meters above the base of the Wapiti Formation and is well exposed along the Smoky River east of Grande Prairie, south of its merge with the Wapiti River. The boundary consists of massive and amalgamated channel sandstones overlying fine grained alluvial plain facies (i.e., overbank, crevasse splays, channel margin, and paleosols) (Figs. 5 and 6C). This sandy interval is dominated by decametre-thick, channel remnants with sheet-like to lenticular geometries. It reaches an overall thickness of 40 meters and suggests deposition under very low accommodation conditions (Fig. 6D). Paleocurrent patterns change across units 2 and 3. Measurements indicate east-west oriented flows in unit 3 (between SU2 and SU3), whereas other Wapiti deposits display an almost uniform south-north pattern. In fact, a south-north pattern for sediment transportation would reflect a trend normal to the progradation of the flexural hingeline during the Campanian-Maastrichtian interval, thus indicating *upstream control* on sediment dispersal patterns (Fig. 3). In contrast, a west-east oriented sediment transportation would be justified only by a nearby major depocenter as in the case of the inland Bearpaw seaway and consequent downstream control.

4.3. Transition between unit 3 and 4 - SU3.

The top of unit 3 marks an abrupt transition from high to low accommodation conditions as well as a major shift in the channel-overbank ratio. Unit 3 is characterized by fine-grained deposits that accumulated on an aggrading coastal plain. Sands were deposited in meandering channels and are interbedded with widespread coal beds and peat, well-developed paleosols, and bentonites, together indicating high-accommodation conditions. In constrast, strata above the unconformity are fluvial facies dominated by ripple-laminated, tabular sandstones, and a stacked-paleochannel architecture which record an abrupt decrease in accommodation (Fig. 6E). In subsurface, this unconformity correlates to a blocky, low gamma ray response that occurs at approximately 360 meters above the base of the Wapiti Formation. As for the transition between unit 2 and 3, paleocurrent measurement indicate a shift in the flows pattern, from a west-east trend below the unconformity to a north-west predominant flow above the contact. Best exposures of this unconformity are located at the Kleskun Hill Park (north east of Grande Prairie) and along the Wapiti River.

4.4. Transition between unit 5 and the Entrance Member (lower Scollard Formation) – SU5.

The contact between the Cutbank coal zone at the top of unit 5 and the overlying Entrance Member (Scollard Formation, Dawson et al., 1994a), is commonly abrupt and easy to define in both outcrop and subsurface. Exposures of this contact display fine-grained, organic-rich, coal bearing strata of unit 5 cut by massive, highly cemented, brownish to light grey, coarse grained sandstone beds referred to the Entrance Member (Fig. 6F). Paleocurrent measurements from tabular and trough cross-stratified structures indicate predominant north-oriented flows in unit 5 deposits, whereas Entrance beds display a N70W flows direction.

This upper boundary of the Wapiti Formation crops out along both flanks of the Cutbank River and in several roadcuts along the Highway 40 South between Grande Prairie and Grande Cache.

5. WAPITI COALS AS SEQUENCE BOUNDARIES

Within the Wapiti Formation, four discrete stratigraphic intervals are characterized by regionally extensive, meter-thick coal beds, whose occurrence has been largely documented in both outcrop and subsurface: in ascending order, the major coal bearing units are: the Basal coals (unit

1), the coal seams of unit 3, and the Red Willow and Cutbank coal zones, respectively, at the top of units 4 and 5.

The basal coals are comparable in age and thickness to the McKay Coal Zone of the Foremost Formation (basal Belly River Group; Gleddie, 1949; Hamblin and Abrahamson, 1996; Beaton et al., 2006). Palynological studies carried out by Dawson et al. (1994a) indicate that this coaly interval contains a middle-late Campanian assemblage that falls within the *Aquilapollinites trialatus* Zone (Sweet et al., 1989). Consequently, coals are coeval with the lower Belly River Group as well as lower Brazeau Formation. Basal coal beds represent the first major coal and peat accumulation within coastal plain sediments of the Wapiti Formation.

The occurrence of the zonal index species *Scollardia trapaformis* and *Mancicorpus gibbus* (early Maastrichtian) indicate that the Cutbank coals are approximately coeval to the Carbon and Thompson coal zones of the Alberta plains (Gibson, 1977; McCabe et al., 1989), as well as to the Whitemud and Battle formations (Srivastava, 1970; Dawson et al., 1994a, b; Braman and Sweet, 1999; Eberth, 2002), thus suggesting a tectonically influenced reduction in sediment supply and a major environmental shift on a basin scale.

In contast, radioisotopic, paleontological, and palynological data provide evidences that coal beds of unit 3 and the Red Willow coal zone represent inland expression of maximum flooding surfaces and therefore are also interpreted as genetic sequence boundaries (*sensu* Galloway, 1989).

5.1 Unit 3 coals

Fine-grained deposits of unit 3 are characterized by the occurrence of three tabular, meter-thick coal beds overlying well-developed reddish peat deposits (**Fig**. 7A). Coals are frequently interbedded with bentonites, organic-rich mudstones, and are commonly capped by widespread and heavily rooted paleosols. The pronounced change in fluvial architecture from amalgamated sand sheet to meandering channel system suggest that upper unit 3 accumulated under increasing accommodation concomitant with the coeval Bearpaw transgressive event. In addition, a bentonite layer occurs within the coal-bearing interval yielded an $^{40}Ar/^{39}Ar$ age of 73.77 ± 1.46 My (David Eberth, pers. comm. 2006). This age is consistent with the 73.4 My age reported by Obradovich (1993) for the maximum transgression of the Bearpaw Seaway in central Alberta (*Baculites compressus* zone, Gill and Cobban, 1973). In the Edmonton area, the transitional facies separating the Bearpaw shales and the overlying beds of the Horseshoe Canyon Formation are characterized by two widespread coal zones, the Basal and the Drumheller coal zones, separated by the lower and upper Bearpaw Marine Tongue (Chen et al., 2005). Coal deposition resulted from the gradual and repeated shifting of facies between the Bearpaw marine tongues and the Horseshoe Canyon non-marine deposits: such interval is characterized by at least five major flooding surfaces, of which the lowermost represent the Bearpaw maximum flooding surface and can be traced across most of the WIB, including west-central Alberta. The deposits that document the initial Bearpaw transgression are represented by conformable succession associated with coal development in all parts of the basin, including equivalent deposits in northern U.S. (Catunean et al., 1997; Chen et al., 2005; Hanczaryk and Gallaher, 2007).

The sequences of coal bearing strata that are associated with the Bearpaw T-R cycle are illustrated in Fig. 8. The first flooding surface of the Bearpaw Sea has been chosen as reference datum, and also marks the MFS of which coal seams of unit 3 are the inland correlative expression. This cross section also illustrates the occurrence of widespread coals associated with regressive transitional deposits that correlate with the lowermost Horseshoe Canyon Formation beds and coal zone. Coal distribution, as well as regional nomenclatural differences, reflects different timing of the south-eastward withdrawal of the inland Bearpaw seaway along the eastern margin of the basin.

5.2 Red Willow Coal Zone

The Red Willow coals occur in the upper 40 meters of unit 4 and are conformably overlain by fine-grained alluvial facies of unit 5 which is essentially barren of coal. Coal beds are up to 1.5 meter thick and commonly interbedded with dark grey carbonaceous mudstone (Fig. 7B). With minor exceptions, seams tend to pinch out over relatively small distance and document deposition under high accommodation conditions associated with significant reduction in sediment supply. Palynological, magnetostratigraphic, paleontological, and sedimentological data indicate that the Campanian-Maastrichtian boundary, (70.6 My, Odin and Lamaurelle, 2001; Ogg et al. 2004) lies within coals occurring at the top of unit 4, referred as the Red Willow coal zone (Srivastava, 1970; Dawson et al., 1994a; Fanti and Catuneanu, in prep.). Consequently, these beds are also equivalent in age to Unit 2 of the Horseshoe Canyon Formation (Eberth, 2002), and particularly to the Drumheller Marine Tongue (*Baculites grandis* zone, Gill and Cobban, 1973) that has been recently assessed an age of 70.4 My (Gibson, 1977; Lerbekmo and Braman, 2002; Ogg et al., 2004; Eberth and Deino, 2005; Wu et al., 2007). Similar for coals of unit 3, fluvial-body stacking patterns together with an inferred phase of high water table conditions suggest a strong influence of base-level oscillation associated with the Drumheller Marine Tongue transgression in central Alberta.

6. DISCUSSION

Based on the recognition of regionally mappable subaerial unconformities this study reveals that the Wapiti Formation consists of four unconformity-bounded depositional sequences (A-D). In ascending order, Sequence A marks the transition from the underlying marine facies of the Puskwaskau Formation to the Wapiti fluvial beds, and consists of strongly progradational to aggradational (high accommodation) deposits and is bounded at the top by SU1. Sequences B and C consist of amalgamated channel-fill deposits at the base (low accommodation), which grade upwards into more floodplain-dominated successions (high accommodation). Their upper contacts are SU2 and SU3, respectively. Sequence D is dominated by channels and extensive overbank facies, indicating high accommodation and vertical aggradation: this sequence is bounded at top by SU4. Subaerial unconformities that bound these sequences are well documented in the study area as well as in the strike oriented section along the foothill region. SU1, 2, and 4 become conformable facies contacts only in the most distal section of the basin; differently, SU3 is difficult to trace east of the Smoky River valley. Regionally extensive coals of unit 3 and uppermost unit 4 represent conformable facies contact correlative to the Bearpaw Formation and Drumheller Marine Tongue MFS respectively. Therefore, it is possible to refer the stratigraphic interval between such deposits as a genetic stratigraphic sequence (Galloway, 1989). In spite significant problems related to the application of this model (i.e., the occurrence of subaerial unconformities within the sequence, the rate of diachroneity along Dip and Strike, Posamentier and Allen, 1999; Catuneanu, 2006), the basin-wide extent of maximum flooding surfaces in both marine and continental strata of the sedimentary basin represents a powerful tool for long distance correlations.

The conformable transition from the marine shales of the Puskwaksau Formation to the fluvial facies of the Wapiti Formation consists of regressive deltaic deposits that pass gradationally upward into the coaly facies of the Basal coal zone. This sequence shares many similarities with the Lea Park/Pakowki – Belly River transition in central and southern Alberta at approximately 79.1 My (Hamblin and Abrahamson, 1996; Gordon, 2000; Eberth, 2005). In addition, the Basal coal zone is similar in depositional setting and age to the McCay Coal Zone. The uppermost Lea Park Formation, Belly River Group (Foremost, Oldman and Dinosaur formations) and the Bearpaw Formation of central Alberta are here interpreted as correlative to uppermost Puskwaskau Formation and Wapiti lithostratigraphic units 1, 2, and 3. Particularly, the widespread amalgamated channel at the base of unit 3 are tentatively correlated with the Clagett cyclothem maximum regressive surface at the base of the Dinosaur Park Formation (76.4 My, *Baculites scotti* zone, Caldwell et al., 1993). The top of this biozone also marks the boundary between middle and upper Campanian at 76.2 My (Kauffman et al., 1993; Obradovich, 1993).

The MFS of the Bearpaw Formation (73.4 My, Obradovich, 1993; *Baculites compressus* zone, Gill and Cobban, 1973) lies within the fine-grained fluvial deposits in the upper portion of unit 3, that show an overall trend from very low to high accommodation conditions. Regionally extensive coals have been assessed an age of 73.77 ± 1.46 My: in spite a significant error margin, this age is supported by a second $^{40}Ar/^{39}Ar$ age of 73.25 ± 0.25 My from the lowermost beds of overlying unit 4 (Eberth, in Currie et al., 2008). The identification of deposits correlative to the Bearpaw MFS within the Wapiti Formation (coal beds of unit 3), indicate that a conformable facies contact can be used for the formal subdivision of the Belly River and Edmonton clastic prisms in central and north-western Alberta.

The well known formations of the Edmonton Group (i.e., Horseshoe Canyon, Whitemud, and Battle formations) are equivalent to Wapiti unit 4 and 5. Coal-bearing zones restricted to the more distal section (particularly coals #0-10 within the Horseshoe Canyon Formation) are here interpreted as expression of MFS during high-stand conditions. In the Wapiti deposits, such conditions are expressed by overall high accommodation conditions observed in unit 4 channel architecture. Particularly, coal seam #10 of the Horseshoe Canyon Formation is associated with the Drumheller Marine Tongue transgressive event and its MFS (70.4 My, Eberth and Deino, 2005; *Baculites grandis* zone, Gill and Cobban, 1973). In the Wapiti Formation, the Red Willow coals are correlative with the Drumheller Marine Tongue, also marking the Campanian-Maastrichtian boundary (70.6 My). Wapiti unit 5 shows an upward increase in available accommodation that culminate with the Cutbank Coal zone, coeval with the early Maastrichtian Carbon-Thompson coals of central Alberta and most likely with the Whitemud and Battle formations.

The Wapiti Formation is capped by the Entrance Member of the lower Scollard Formation (~67 My), which distribution has been largely documented in different sections of the WIB. Figure 9 illustrates the proposed correlation between sequences identified within the Wapiti succession and correlative deposits of central and southern Alberta.

Discussed lithostratigraphic units and depositional sequences within the Wapiti Formation were described and documented in their lateral variation using several geological approaches, including detailed facies analysis, petrography, palynological and paleontological associations, radioisotopic ages, geophysical well log signature, and sequence stratigraphic approaches. Therefore we propose to consider the Wapiti succession as a Group, raising the previously recognized Wapiti Formation (McLearn, 1919) to Group status.

7. CONCLUSIONS

The along strike structural flexuration of the Alberta foreland basin resulted in an overall south-eastward plunge of the basin in west-central Alberta: the space created from this process was filled by marine deposits to the southeast (Bearpaw Formation), transitional strata in the Edmonton area (Bearpaw-Horseshoe Canyon transition), and by non-marine strata in the Grande Prairie region. In this proximal area, base-level oscillations related to the Bearpaw Seaway transgression resulted in: (1) a shift from *upstream* to *downstream* control in the fluvial architecture and deposition; (2) significant increase in accommodation coupled with higher water table conditions; and (3) reorganization of the fluvial drainage system from an overall northward directed trend to an eastward directed system. Remarkably, according to paleogeographic maps for the Bearpaw time (Dawson et al., 1994b), Wapiti coals deposited approximately 250 km inland from the reconstructed shoreline in the Edmonton region and therefore represent a case study to support the utility of regionally extensive coal seams as stratigraphic markers. This study shows the coal seams to mark regionally significant maximum flooding surfaces that can be tied to marine transgressions.

As pointed out by Eberth (2002), although changes in sediment supply, accommodation, base-level oscillation, and climate may result in dramatic variations within and between units, the co-occurrence of the expression of such parameters at a basin scale suggests strong genetic correlations. This study indicates that previously identified lithostratigraphic units in the Campanian-Maastrichtian Wapiti Formation of western-central Alberta also provide fundamental information for a sequence stratigraphic interpretation of the Wapiti clastic system. Particularly,

1. Facies analysis, palynological and subsurface data document four regionally mappable subaerial unconformity that delimit unconformity bounded depositional sequences (Sequences A-D). Overall they consist of fining upward alluvial deposits characterized by amalgamated channel-fill beds at the base (low accommodation) which grade upwards into more floodplain-dominated successions (medium- to high-accommodation).

2. The maximum flooding surface of the Bearpaw seaway, which is a reference marine unit in central and southern Alberta, lies within the fine-grained fluvial deposits in the upper portion of Sequence C (lithostratigraphic unit 3). Within Sequence D, the Red Willow Coal zone is age-equivalent to the Drumheller Marine Tongue transgressive event and marks another maximum flooding surface within the fluvial deposits of the Wapiti Formation. Therefore, this study supports the utility of regional coals as conformable genetic sequence boundaries in non-marine successions.

3. The identification of regionally mappable lithostratigraphic units and time significant sequence boundaries within the Wapiti succession, whose description and extent is consistent across all data types and analyses, support to elevation of Wapiti Formation to Group status.

ACKNOWLEDGEMENTS

The authors thank the Paleontological Society of The Peace and the Grande Prairie Regional College for their fundamental support in the field. Also, thanks to G.B. Vai, L. Bonach, and A. Mumpy. Funding to F.F. was provided by the Jurassic Foundation, the Dinosaur Research Institute, the Fondazione Cassa di Risparmio in Bologna, the Bologna University and the Museum of Geology and Paleontology Giovanni Capellini (Bologna).

References:

AMOROSI, A., COLALONGO, M., 2005, The linkage between alluvial and coeval nearshore marine successions: evidence from the Late Quaternary record of the Po River Plain, Italy, *in* Blum, M., Marriott, S., and Leclair, S., eds., Fluvial Sedimentology VII: International Association of Sedimentologists Special Publication 35, p. 257–275.

BEATON, A., LANGERBERG, W., AND PANA, C., 2006, Coalbed methane resources and reservoir characteristics from the Alberta Plains, Canada: International Journal of Coal Geology, v. 65, p. 93-113.

BLUM, M., AND TORNQVIST, T., 2000, Fluvial response to climate and sea-level change: a review and look forward: Sedimentology , v. 47, p. 2-48.

BRAMAN, D., AND SWEET, A., 1999, Terrestrial palynomorph biostratigraphy of the Cypress Hills, Wood Mountain, and Turtle Mountain areas (Upper Cretaceous-Paleocene) of western Canada: Canadian Journal of Earth Sciences, v. 36, p. 725-741.

BUSTIN, R., AND SMITH, G., 1993, Coal deposits in the Front Ranges and Foothills of the Canadian Rocky Mountains, southern Canadian Cordillera: International Journal of Coal Geology, v. 23, p. 1-27.

CALDWELL, W., DINER, R., EICHER, D., FOWLER, S., NORTH, B., STELCK, C., AND VON HOLDT, W., 1993, Foraminiferal biostratigraphy of Cretaceous marine cyclothems, *in* Caldwell, W., and Kauffman, E., eds., Evolution of the Western Interior Basin: Geological Association of Canada Special Paper 39, p. 477-520.

CANT, D., AND STOCKMAL, G., 1989, The Alberta foreland basin: relationship between stratigraphy and Cordilleran terrane-accretion events: Canadian Journal of Earth Sciences, v. 26, p. 1964-1975.

CATUNEANU, O., SWEET, A., AND MIALL, A., 1997, Reciprocal architecture of Bearpaw T-R sequences, uppermost Cretaceous, Western Canadian Sedimentary Basin: Bulletin of Canadian Petroleum Geology, v. 45, p. 75-94.

CATUNEANU, O., AND SWEET, A., 1999, Maastrichtian-Paleocene foreland-basin stratigraphies, western Canada: a reciprocal sequence architecture: Canadian Journal of Earth Sciences, v. 36, p. 685-703.

CATUNEANU, O., SWEET,A., MIALL, A., 1999, Concepts and styles of reciprocal stratigraphies: Western Canada foreland system: Terra Nova, v. 11, p. 1-8.

CATUNEANU, O., SWEET, A., AND MIALL, A., 2000, Reciprocal stratigraphy of the Campanian-Paleocene Western Interior of North America: Sedimentary Geology, v. 134, p. 235-255.

CATUNEANU O., AND ELANGO, H., 2001, Tectonic control on fluvial styles: the Balfour Formation of the Karoo Basin, South Africa: Sedimentary Geology, v. 140, p. 291-313.

CATUNEANU, O., KHIDIR, A., AND THANJU, R., 2003, External controls on fluvial facies: the Scollard sequence, Western Canada foredeep: American Association of Petroleum Geologists Annual Convention, Salt Lake City, Official Program, v. 12, A27.

CATUNEANU, O., 2002, Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls: Journal of African Earth Sciences, v. 35, p. 1-43.

CATUNEANU, O., 2006, Principles of sequence stratigraphy: Elsevier Publisher, Amsterdam, 375 p.

CHEN, D., AND BERGMAN, K., 1999, Stratal reorientation, depositional processes, and sequence evolution of the Cretaceous in the Peace River Arch region of the Western Canada Sedimentary Basin: Bulletin of Canadian Petroleum Geology, v. 47, p. 594-620.

CHEN, D., LANGEBERG, W., AND BEATON, A., 2005, Horseshoe Canyon – Bearpaw transition and correlation of associated coal zones across the Alberta Plain: Alberta Energy and Utilities Board, EUB/AGS Geo-Note 2005-08, 22 p.

CURRIE, P., LANGSTON, W., AND TANKE, D., 2008, A New Horned Dinosaur from an Upper Cretaceous Bonebed in Alberta: National Engineering Council Research Press, Ottawa. 152 pp.

DAHLE, K., FLESIA, K., TALBOT, M., AND DREYER, T., 1997, Correlation of fluvial deposits by the use of Sm-Nd isotope analysis and mapping of sedimentary architecture in the Escanilla Formation (Ainsa Basin, Spain) and the Statfjord Formation (Norwegian North Sea): Abstracts, Sixth International Conference on Fluvial Sedimentology, Cape Town, 46 p.

DAWSON, F., KALKREUTH, W., AND SWEET, A., 1994a, Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta: Geological Survey of Canada Bulletin, v. 466, 60 p.

DAWSON, F., EVANS, C., MARSH, R., AND RICHARDSON, R., 1994b, Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin, *in* Mossop, G., and Shetson, I., eds., Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, chapter 24, 18 p.

EBERTH, D., AND HAMBLIN, A., 1993, Tectonic, stratigraphy, and sedimentologic significance of a regional discontinuity in the upper Judith River Group (Belly River wedge) of southern Alberta, Saskatchewan, and northern Montana: Canadian Journal of Earth Sciences, v. 30, p. 174-200.

EBERTH, D., AND DEINO, A., 2005, New $^{40}Ar/^{39}Ar$ ages from three bentonites in the Bearpaw, Horseshoe Canyon, and Scollard formations (Upper Cretaceous-Paleocene) of southern Alberta, *in* Braman, D., Therrien, F., Koppelhus, E., and Taylor, W., eds., Dinosaur Park Symposium - Short Papers, Abstracts and Program: Special Publication of the Royal Tyrrell Museum, p. 23-24.

EBERTH, D., 1996, Origin and significance of mud-filled incised valleys (Upper Cretaceous) in southern Alberta, Canada: Sedimentology, v. 43, p. 449-477.

EBERT, D., 2002, Review and comparison of Belly River Group and Edmonton Group stratigraphy and stratigraphic architecture in the Southern Alberta Plains: Canadian Society of Petroleum Geologists, Diamond Jubilee Convention, Program and Abstract 117, Abstracts of Technical Talks, Poster and Core Displays including Extended abstracts, PDF file 227S0125 CD.

EBERTH, D., 2005, The geology, *in* Currie, P., and Koppelhus, E., eds., Dinosaur Provincial Park, a spectacular ecosystem revealed: Indiana university Press, Bloomington, chapter 3, p. 54-82.

FANTI, F., 2007, Unfolding the geological history of the North: new comprehensive survey of the Wapiti Formation, Alberta, *in* Braman, D., ed., Ceratopsian Symposium, Short Papers, Abstracts, and Programs, p. 33-38.

FLORES, R., 1984, Comparative analysis of coal accumulation in Cretaceous alluvial deposits, southern united States Rocky Mountain Basin, *in* Stott, D., and Glass, D., eds., The Mesozoic of Middle North America. Canadian Society of Petroleum Geologist Memoir, 9, p. 373-387.

GALLOWAY, W., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units: AAPG Bulletin, v. 73, p. 125-142.

GIBSON, D., 1977, Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River Valley, Alberta: Geological Society of Canada, Paper 76-35, 41 p.

GILL, J., AND COBBAN, W., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: United States Geological Survey, Professional Paper 776.

GLEDDIE, J., 1949, Upper Cretaceous in Western Peace River Plains, Alberta: Bulletin of the American Association of Petroleum Geologists, v. 33, p. 511-532.

GORDON, J., 2000, Stratigraphy and sedimentology of the Foremost Formation in southeastern Alberta and southwestern Saskatchewan: M. Sc. Thesis, University of Regina, Regina, Saskatchewan, 75 p.

HAMBLIN, A., AND ABRAHAMSON, B., 1996, Stratigraphic architecture of "Basal Belly River" cycles, Foremost Formation, Belly River Group, subsurface of southern Alberta and southwestern Saskatchewan: Bulletin of Canadian Petroleum Geology, v. 44, p. 654-673.

HAMBLIN, A., 1997a, Stratigraphic architecture of the Oldman Formation, Belly River Group, surface and subsurface of southern Alberta: Bulletin of Canadian Petroleum Geology, v. 45(2), p. 155-177.

HAMBLIN, A., 1997b, Regional distribution and dispersal of the Dinosaur Park Formation, Belly River Group, surface and subsurface of southern Alberta: Bulletin of Canadian Petroleum Geology, v. 45, p. 377-399.

HAMILTON, D., AND TADROS, N., 1994, Utility of coal seams as genetic stratigraphic sequence boundaries in non-marine basins: an example from the Gunnedah Basin, Australia: AAPG Bulletin, v. 78, p. 267-286.

HANCZARYK, P., AND GALLAHER, W., 2007, Stratigraphy and paleoecology of the middle Pierre Shale along the Missouri River, central South Dakota: Geological Society of America – Special Paper, v. 427, p. 51-69.

JERVEY, M., 1988, Quantitative geological modelling of siliciclastic rock sequences and their seismic expression, *in* Wilgus, C., Hastings, C., Kendall, C., Posamentier, H., Ross, C., and Van Wagoner, J., eds., Sea level changes, an integrated approach: SEPM Special Publication, 42, p. 47-69.

JERZYKIEWICZ, T., 1985a, Tectonically deformed pebbles in the Brazeau and Paskapoo formations, central Alberta foothills, Canada: Sedimentary Geology, v. 42, p. 159-180.

JERZYKIEWICZ, T., 1985b, Stratigraphy of the Saunders Group in the central Alberta Foothills - a progress report: Geological Survey of Canada, Current Research, Part B, Paper 85-1B, p. 247-258.

JERZYKIEWICZ, T., AND SWEET, A., 1988, Sedimentological and palynological evidence of regional climatic changes in Campanian to Paleocene sediments of the Rocky Mountain Foothills, Canada: Sedimentary Geology, v. 59, p. 29-76.

JERZYKIEWICZ, T., AND McLEAN, J., 1980, Lithostratigraphical and sedimentological framework of coal-bearing Upper Cretaceous and lower Tertiary strata, Coal Valley Area, Central Alberta Foothills: Geological Survey of Canada, Paper 79-12, 47 p.

KAUFFMAN, E., SAGEMAN, B., KIRKLAND, J., ELDER, W., HARRIES, P., AND VILLAMIL, T., 1993, Molluscan biostratigraphy of the Cretaceous Western Interior Basin, North America, *In* Caldwell, W., and Kauffman, E., eds., Evolution of the Western Interior Basin, Geological Association of Canada Special Paper, v. 39, p. 397-434.

LERBECKMO, J., AND BRAMAN, D., 2002, Magnetostratigraphic and biostratigraphic correlation of late Campanian and Maastrichtian marine and continental strata from the Red Deer Valley to the Cypress hill, Alberta, Canada: Canadian Journal of Earth Sciences, v. 39, p. 539-557.

MACK, G., AND JERZYKIEWICZ, T., 1989, Provenance of post-Wapiabi sandstones and its implications for Campanian to Paleocene tectonic history of the southern Canadian Cordillera: Canadian Journal of Earth Sciences, v. 26, p. 665-676.

MARRIOTT, S., 1999, The use of models in the interpretation of the effects of base-level change on alluvial architecture, *In* Smith, N., and Rogers, J., eds., Fluvial Sedimentology VI: International Association of Sedimentology Special Publication, 28, p. 271-281.

McCABE, P., STROBL, R., MACDONALD, D., NURKOWSKI, J., AND BOSMAN, A., 1989, An evaluation of the coal resources of the Horseshoe Canyon Formation and laterally equivalent strata to a depth of 400 meters, in the Alberta plains area: Alberta Research Council, Open File Report 1987-07.

McLEARN, F., 1919, Cretaceous, Lower Smoky River, Alberta: Geological Survey of Canada, Summary Report, Part C, p. 17.

MIALL, A., 1991, Stratigraphic sequences and their chronostratigraphic correlation: Journal of Sedimentary Petrology, v. 61, p. 497-505.

MIALL, A., AND ARUSH, M., 2001, Cryptic sequence boundaries in braided fluvial successions: Sedimentology, v. 48, p. 971-985.

NEMEC, W., 1988, Coal correlations and intrabasinal subsidence: a new analytical perspective, *in* Kleinspehn, K., and Paola, C., eds., New Perspectives in Basin Analysis: Springer-Verlag, New York, p. 161-188.

NURKOWSKI, J., AND RAHAMANI, R., 1984, An Upper Cretaceous fluvio-lacustrine coal-bearing sequence, Red Deer Area, Alberta, Canada: Spec. Publs. Int. Ass. Sediment, v. 7, p. 163-176.

OBRADOICH, J., 1993, A Cretaceous time-scale, *in* Caldwell, W., and Kauffman, E., eds., Evolution of the Western Interior Basin: Geological Association of Canada Special Paper, 39, p. 379-396.

ODIN, G., AND LAMURELLE, M., 2001, The global Campanian-Maastrichtian stage boundary: Episodes, v. 24, p. 229–238.

OGG, J., AGTERBERG, F., AND GRADSTEIN, F., 2004, The Cretaceous Period, *in* Gradstein, F,. Ogg, J., and Smith, A., eds., A Geologic time scale: Cambridge University Press, Cambridge, p. 344-383.

OLSEN, T., STEEL, R., HOGSETH, K., SKAR, T., AND ROE, S., 1995, Sequential architecture in a fluvial succession: sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon, Utah: Journal of Sedimentary Research, p. 265-280.

POSAMENTIER, H., 1991, Lowstand alluvial bypass systems: incised vs. unincised: AAPG, Bulletin, v. 85, p. 1771-1793.

POSAMENTIER, H., AND VAIL, P., 1988, Eustatic controls on clastic deposition II - Sequence and systems tract models, *in* Wilgus, B., Hastings, B., Kendall, C., Posamentier, H., Ross, C., and Van Wagoner, J., eds., Sea Level Changes: An Integrated Approach. SEPM Special Publication, 42, p. 125-154.

POSAMENTIER, H., JERVEY, M., AND VAIL, P., 1988, Eustatic controls on clastic deposition I – conceptual framework, *in* Wilgus, C., Hastings, C., Kendall, C., Posamentier, H., Ross, C., and Van Wagoner, J., eds., Sea level changes, an integrated approach: SEPM Special Publication, 42, p. 125-154.

POSAMENTIER, H., AND ALLEN, G., 1993, Variability of the sequence stratigraphic model: effects of local basin factors: Sedimentary Geology, v. 86, p. 91-109.

POSAMENTIER, H. AND ALLEN, G., 1999, Siliciclastic Sequence Stratigraphy – Concepts and Applications: SEPM, Concepts in Sedimentology and Paleontology, v. 7, 210 p.

PRICE, R., 1994, Cordilleran tectonics and the evolution of the Western Canadian Sedimentary Basin, *in* Mossop, G., and Shetson, I., eds., Geological Atlas of the Western Canada Sedimentary Basin: Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, Chapter 2, p. 13-24.

ROGERS, R., 1998, Sequence analysis of the Upper Cretaceous Two Medicine and Two Medicine formations, Montana: nonmarine response to the Claggett and Bearpaw marine cycles: Journal of Sedimentary Research, v. 68, p. 615-631.

ROGERS, R., SWISHER III, C., AND HORNER, J., 1993, $^{40}Ar/^{39}Ar$ age and correlation of the nonmarine Two Medicine Formation (Upper Cretaceous), northwestern Montana, U.S.A.: Canadian Journal of Earth Sciences, v. 30, p. 1066-1075.

SCHUMM, S., 1993, River Response to base level change: implication for sequence stratigraphy: The Journal of Geology, v. 101, p. 279-294.

SHANLEY, K., McCABE, P., AND HETTINGER, R., 1992, Significance of tidal influence in fluvial deposits from interpreting sequence stratigraphy: Sedimentology, v. 39, p. 905-930.

SHANLEY, K., AND McCABE, P., 1994, Perspective on the Sequence Stratigraphy of continental strata: AAPG, Bulletin, v. 78, p. 544-568.

SHANLEY, K., AND McCABE, P., eds., 1998, Relative role of eustasy, climate, and tectonism in continental rocks: SEPM Special Publication, 59, 234 p.

SRIVASTAVA, S., 1970, Pollen biostratigraphy and paleoecology of the Edmonton Formation (Maestrichtian), Alberta, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 7, p. 221-276.

SWEET, A., RICKETTS, B., CAMERON, A., AND NORRIS, D., 1989, An integrated analysis of the Brackett coal basin, Northwest Territories: Geological Survey of Canada, Paper 89-1, p. 85-89.

TIBERT, N., AND GIBLING, M., 1999, Peat accumulation on a drowned coastal braidplain: the Mullins Coal (Upper Carboniferous), Sydney Basin, Nova Scotia: Sedimentary Geology, v. 128, p. 22-38.

TYE, R., AND KOSTERS, E., 1986, Style of interdistributary basin sedimentation: Mississippi delta Plain, Louisiana: Transaction of the Gulf Coast Association of Geological Societies, v. 36, p. 575-588.

WADSWORTH, J., BOYD, R., DIESSEL, C., LECKIE, D., AND ZAITLIN, B., 2002, Stratigraphic style of coal and non-marine strata in a tectonically influences intermediate accommodation setting: the Mannville Group of Western Canadian Sedimentary Basin, south-central Alberta: Bulletin of Canadian Petroleum Geology, v. 50, p. 507-541.

WOOD, L., ETHRIDGE, F., AND SCHUMM, S., 1993, The effects of rate of base level fluctuations on coastal plain, shelf and slope depositional systems: an experimental approach, *in* Posamentier, H., Summerhayes, C., Haq, B., and Allen, G., eds., Sequence Stratigraphy and Facies Associations: International Association of Sedimentologists Special Publication, 18, p. 43-53.

WU, X., BRINKMAN, D., EBERTH, D., AND BRAMAN, D., 2007, A new ceratopsid dinosaur (Ornithiscia) from the uppermost Horseshoe Canyon Formation (upper Maastrichtian), Alberta, Canada: Canadian Journal of Earth Sciences, v. 44, p.1243-1265.

ZDRAVKOV, A., KOSTOVA, I., SACHSENHOFER, R., AND KORTENSKI, J., 2006, Reconstruction of paleoenvironment during coal deposition in the Neogene Karlovo graben, Bulgaria: International Journal of Coal Geology, v. 67, p. 79-94.

Figure Caption:

Figure 1: Regional map of the study area showing outline of the Wapiti Formation and correlative middle Campanian to early Maastrichtian successions in the Alberta foreland basin.

Figure 2: Selected Campanian and Maastrichtian lithostratigraphies in the Western Interior Basin. Sources: Alaska and west-central Alberta, Fanti, 2007, Currie et al., 2008; central-southern Alberta, Eberth and Deino, 2005, Eberth, 2005, Mumpy and Catuneanu, 2007; north-western Montana, Rogers et al., 1993.

Figure 3: Foredeep position during consecutive time slice of the early Campanian – late Maastrichtian interval in the evolution of the Alberta Foreland system (modified after Catuneanu, 2004). Arrows indicate main direction of load shift. EC, early Campanian; MC, middle Campanian; LC, late Campanian; EM, early Maastrichtian; LM, late Maastrichtian.

Figure 4: Along-strike stratigraphic cross-section in the Alberta foothills region documenting the south-eastward plunge of the foreland basin. A, present day depth of lower and middle Campanian succession. B, reconstructed middle Campanian thicknesses of pre- and syn-Bearpaw successions. The proximal and distal sections of the basin differ in thickness of almost 200 meters that accumulated in the eastern margin mostly during the tectonically induced Bearpaw transgressive event.

Figure 5: A, cross-section (gamma-ray) showing the contact between the marine Puskwaskau Formation and the fluvial Wapiti Formation. The basal Wapiti beds are characterized by the regionally extended Basal coal and Basal Coal Zone (see the text for discussion). SU1 marks the contact between lithostratigraphic unit 1 and 2. Dashed lines indicate bentonites. B, cross-section (gamma-ray) illustrating lateral continuity of SU1 and SU2 from the Grande Prairie region to central Alberta. Widespread, amalgamated channel sandstone occur at the base of unit 2 and 3. Predominant paleocurrent directions are represented by rose diagrams. Dashed line indicates bentonites.

Figure 6: A, normal regressive deltaic deposits at the Puskwaskau-Wapiti transition (Belcourt Creek, British Columbia); B, SU 1, Simonette River. C, SU 2, Smoky River; D,

amalgamated channel at the base of unit 3 (sequence C), Wapiti River; E, SU 3, Wapiti River; F, SU 4 and the contact between coaly facies of Wapiti unit 5 and coarse grained deposits of the Entrance Mbr., Athabasca River, courtesy of Lisa Bonach.

Figure 7: A, tabular coal seams of unit 3 cropping out at the Kleskun Hill Park (north-east of Grande Prairie). Dated bentonitic layer occurs approximately 2 meters below coal #1. B, a couplet of coal seams in the Red Willow Coal Zone interbedded with light coloured carbonaceous mudstone (Pinto Creek).

Figure 8: Cross-section illustrating the stratigraphic occurrence of major coal zones and coal seams with respect to the second order Bearpaw trangressive event. The first flooding surface recognized in the Bearpeaw Formation (73.4 My) is used as stratigraphic datum. Coal seams of unit 3 are interpreted as expression of the Bearpaw MFS, whereas coal zones in the Horseshoe Canyon Formation developed in response to 3rd order flooding event during the Bearpaw high stand phase.

Figure 9: Proposed style of reciprocal stratigraphies of Late Cretaceous successions in the Western Canadian Sedimentary Basin. White areas indicate major clastic wedges, grey areas represent marine sedimentation (modified after Mumpy and Catuneanu, 2007). 1, *Baculites McLearni*, MFS of the Lea Park Formation; 2, *Baculites scotti*, lower boundary of the Bearpaw cycle; 3, *Baculites compressus*, Bearpaw MFS; 4, Drumheller Marine Tongue MFS, 73.4 My. Black boxes indicate major coal zones.

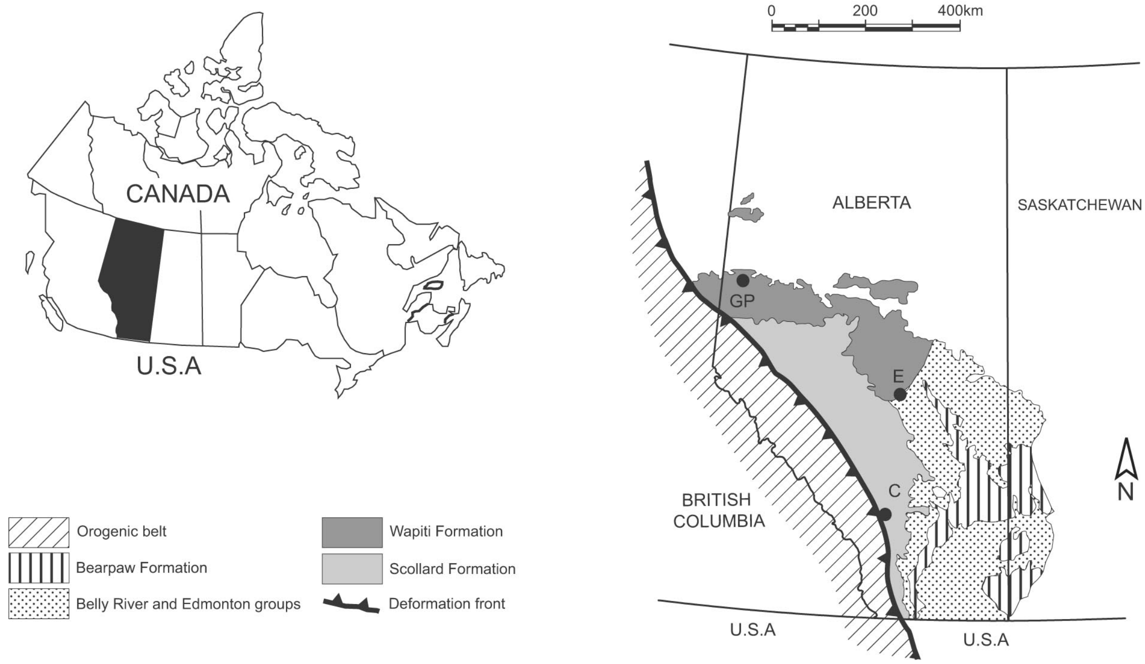
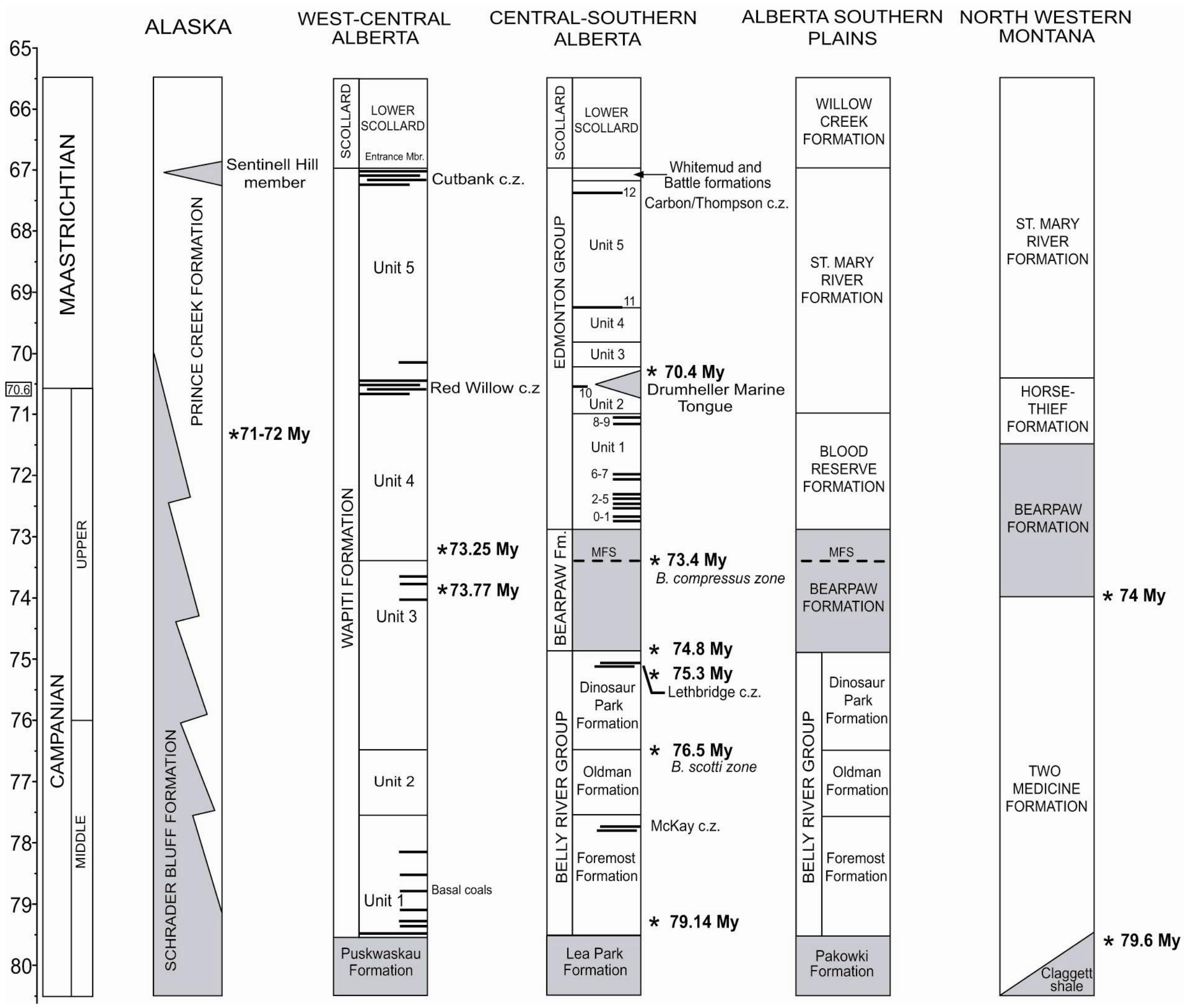
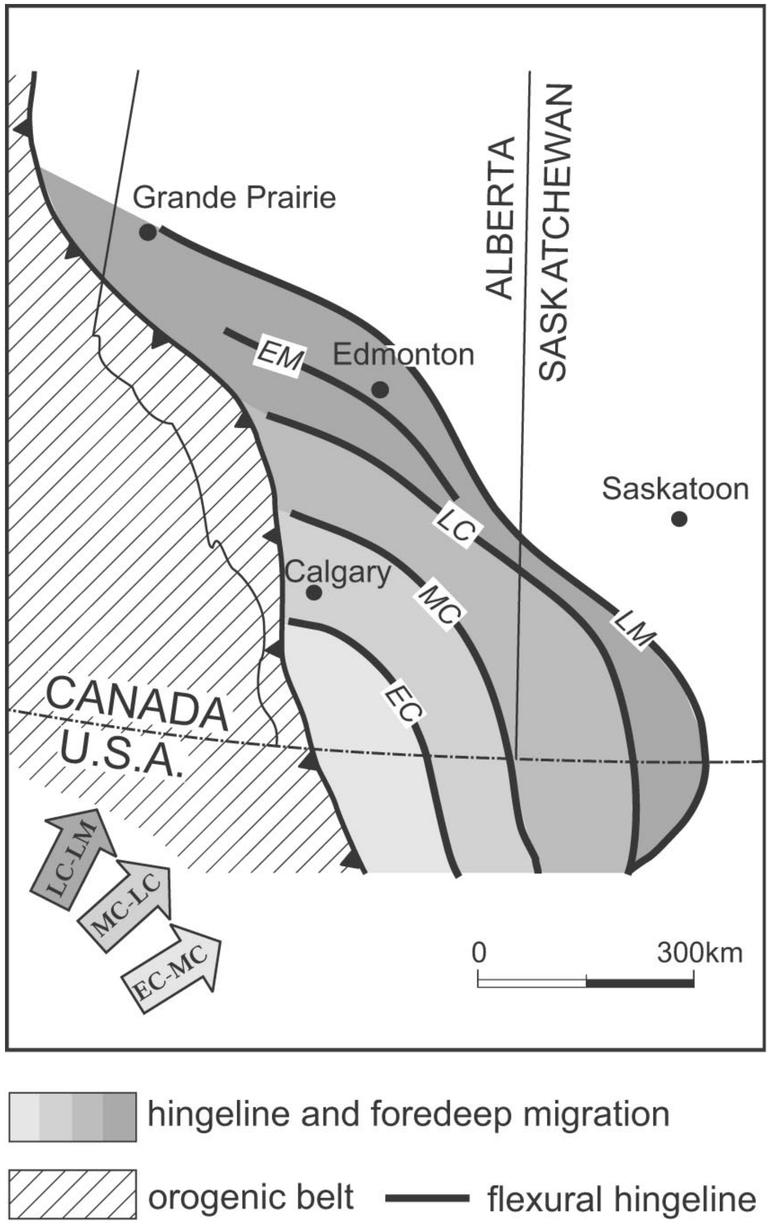

CANADA
U.S.A
0
200
400km
ALBERTA
SASKATCHEWAN
GP
E
C
BRITISH
COLUMBIA
U.S.A
U.S.A
N
Orogenic belt
Bearpaw Formation
Belly River and Edmonton groups
Wapiti Formation
Scollard Formation
Deformation front

Figure 1



ALASKA
WEST-CENTRAL ALBERTA
CENTRAL-SOUTHERN ALBERTA
ALBERTA SOUTHERN PLAINS
NORTH WESTERN MONTANA
MAASTRICHTIAN
CAMPANIAN
UPPER
MIDDLE
70.6
Sentinell Hill member
PRINCE CREEK FORMATION
SCHRADER BLUFF FORMATION
*71-72 My
SCOLLARD
LOWER SCOLLARD
Entrance Mbr.
Cutbank c.z.
Unit 5
Red Willow c.z
Unit 4
WAPITI FORMATION
*73.25 My
*73.77 My
Unit 3
Unit 2
Unit 1
Basal coals
Puskwaskau Formation
Whitemud and Battle formations
Carbon/Thompson c.z.
EDMONTON GROUP
Unit 4
Unit 3
* 70.4 My
Drumheller Marine Tongue
8-9
6-7
2-5
0-1
BEARPAW Fm.
MFS
* 73.4 My
B. compressus zone
* 74.8 My
* 75.3 My
Lethbridge c.z.
Dinosaur Park Formation
* 76.5 My
B. scotti zone
Oldman Formation
McKay c.z.
Foremost Formation
BELLY RIVER GROUP
* 79.14 My
Lea Park Formation
WILLOW CREEK FORMATION
ST. MARY RIVER FORMATION
BLOOD RESERVE FORMATION
BEARPAW FORMATION
Pakowki Formation
HORSE-THIEF FORMATION
* 74 My
TWO MEDICINE FORMATION
* 79.6 My
Claggett shale

Figure 2



Grande Prairie
Edmonton
Saskatoon
Calgary
ALBERTA
SASKATCHEWAN
CANADA
U.S.A.
EM
LC
MC
EC
LM
LC-LM
MC-LC
EC-MC
0
300km
hingeline and foredeep migration
orogenic belt
flexural hingeline

Figure 3

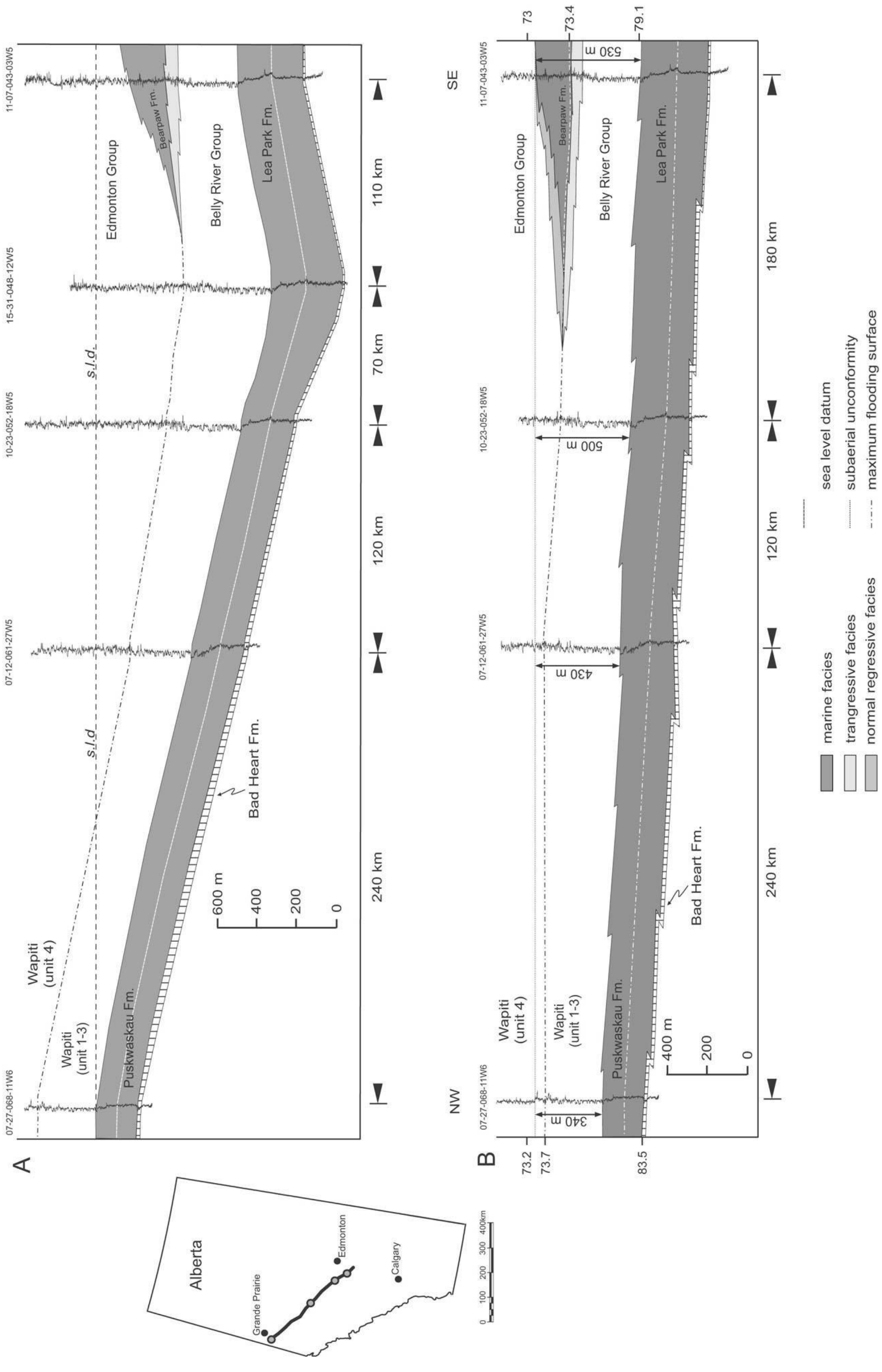

A
B
NW
SE
Alberta
Grande Prairie
Edmonton
Calgary
07-27-068-11W6
07-12-061-27W5
10-23-052-18W5
15-31-048-12W5
11-07-043-03W5
Wapiti (unit 4)
Wapiti (unit 1-3)
Puskwaskau Fm.
Bad Heart Fm.
Edmonton Group
Bearpaw Fm.
Belly River Group
Lea Park Fm.
s.l.d.
240 km
120 km
70 km
110 km
180 km
600 m
400
200
0
400 m
340 m
430 m
500 m
530 m
73.2
73.7
83.5
73
73.4
79.1
marine facies
trangressive facies
normal regressive facies
sea level datum
subaerial unconformity
maximum flooding surface

Figure 4

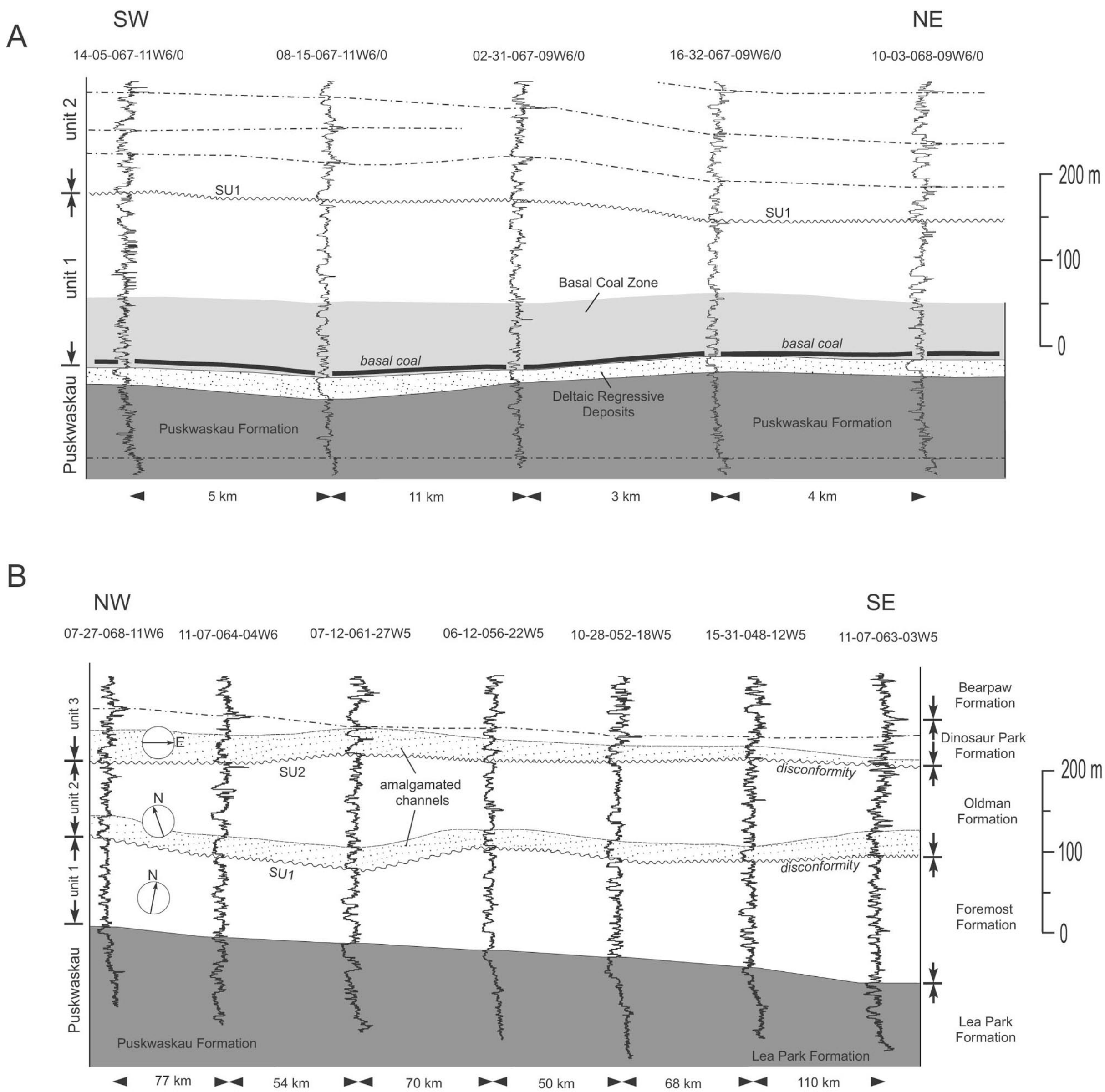

A
SW
NE
14-05-067-11W6/0
08-15-067-11W6/0
02-31-067-09W6/0
16-32-067-09W6/0
10-03-068-09W6/0
unit 2
unit 1
Puskwaskau
SU1
SU1
Basal Coal Zone
basal coal
basal coal
Deltaic Regressive Deposits
Puskwaskau Formation
Puskwaskau Formation
200 m
100
0
5 km
11 km
3 km
4 km
B
NW
SE
07-27-068-11W6
11-07-064-04W6
07-12-061-27W5
06-12-056-22W5
10-28-052-18W5
15-31-048-12W5
11-07-063-03W5
unit 3
unit 2
unit 1
Puskwaskau
E
N
N
SU2
SU1
amalgamated channels
disconformity
disconformity
Puskwaskau Formation
Lea Park Formation
Bearpaw Formation
Dinosaur Park Formation
Oldman Formation
Foremost Formation
Lea Park Formation
200 m
100
0
77 km
54 km
70 km
50 km
68 km
110 km

Figure 5

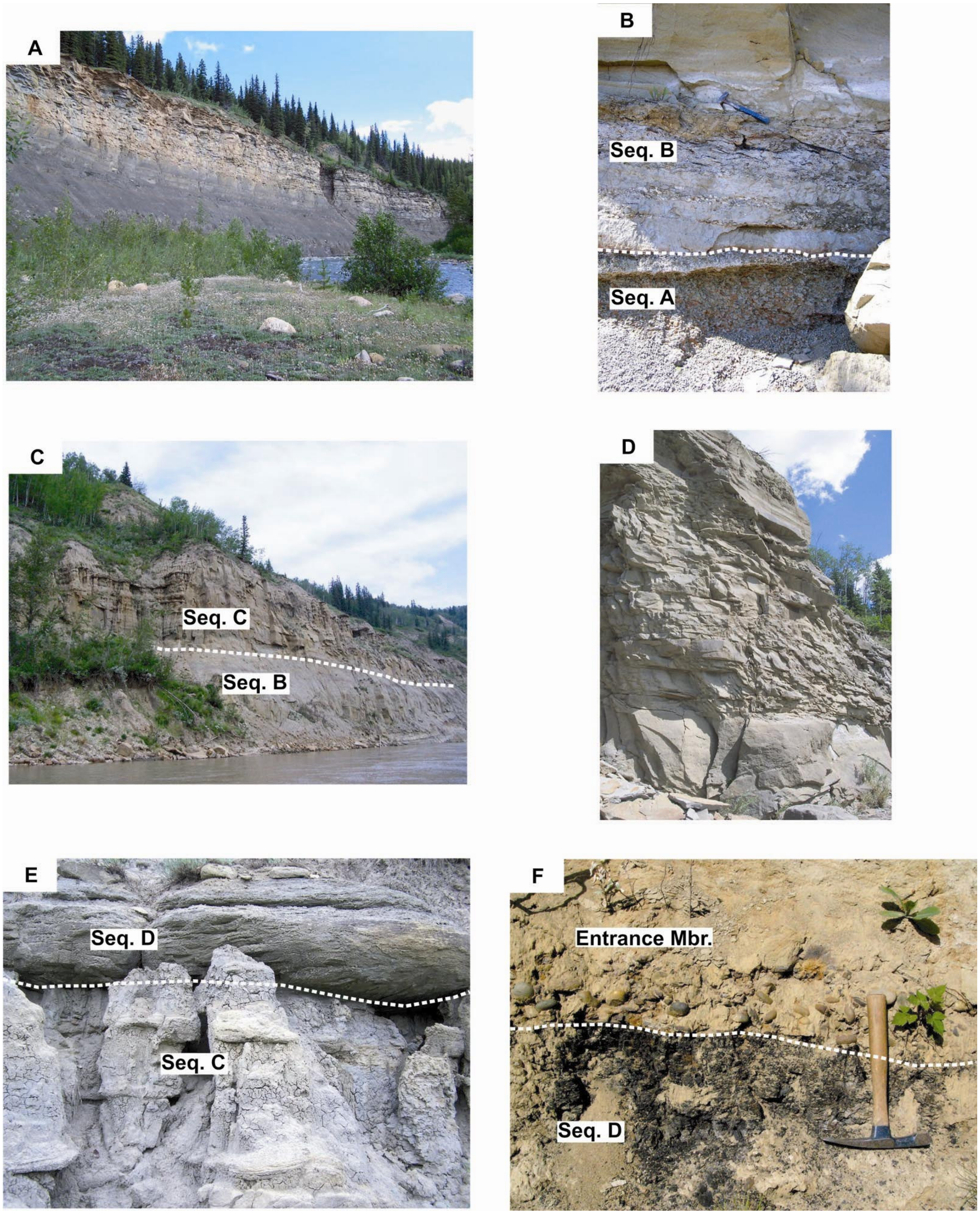


Figure 6

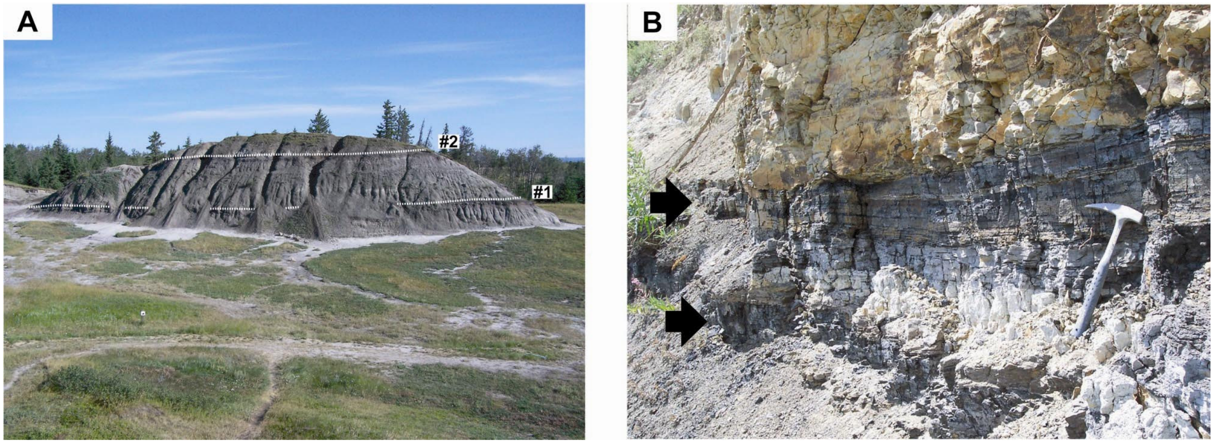
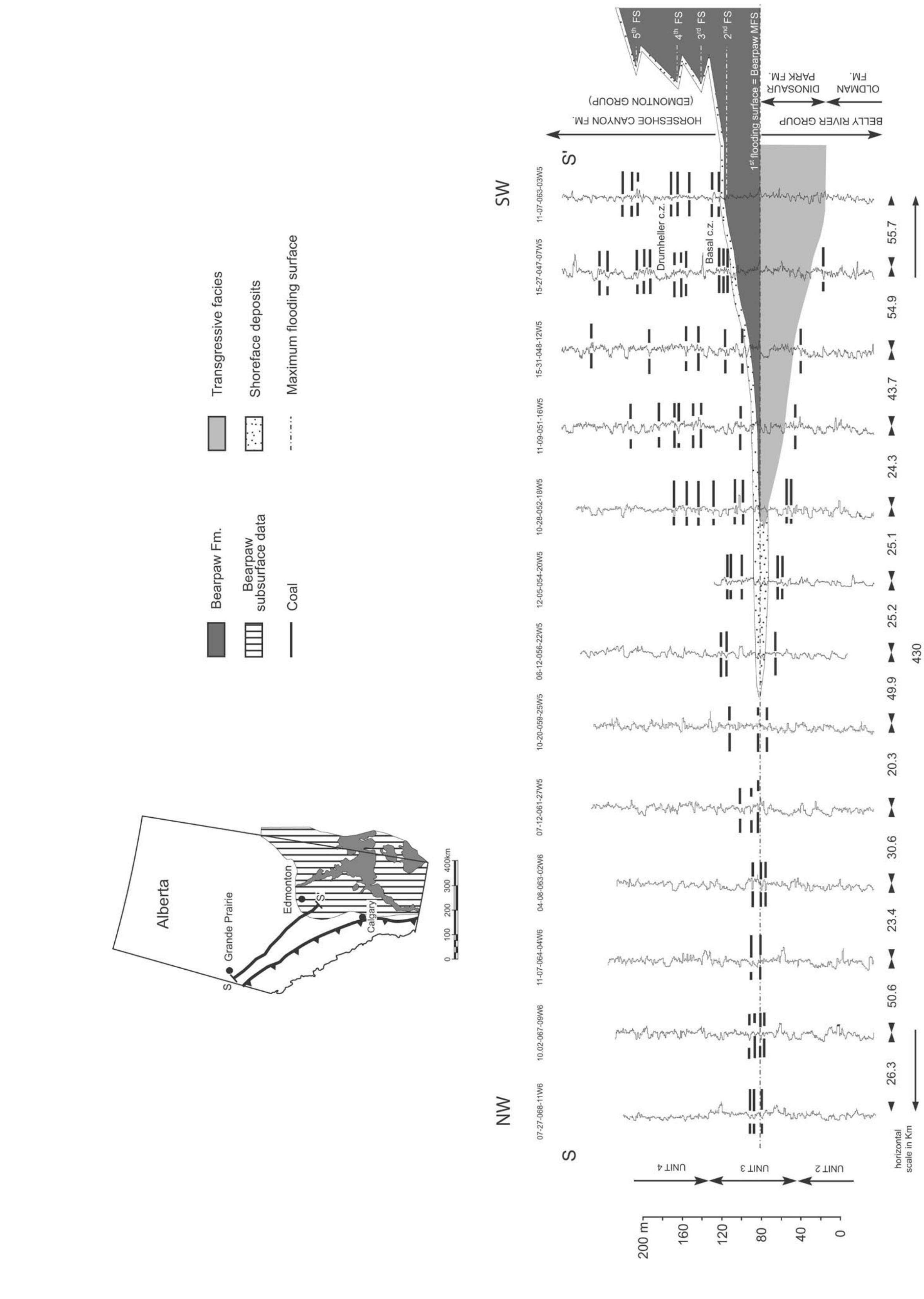
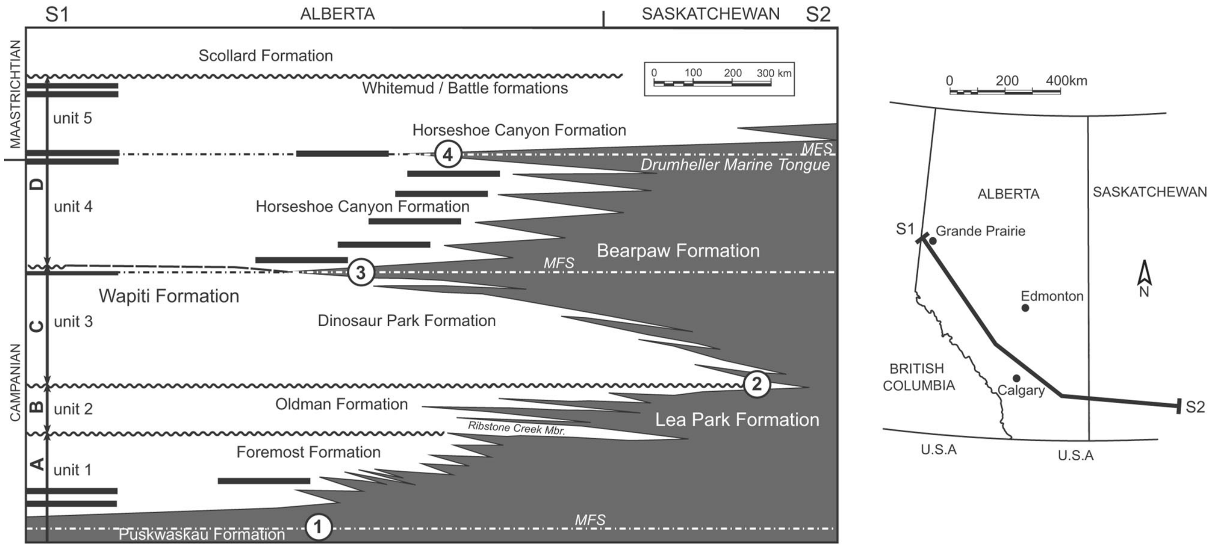


Figure 7



Alberta
Grande Prairie
Edmonton
Calgary
S
S'
0 100 200 300 400km
Bearpaw Fm.
Bearpaw subsurface data
Coal
Transgressive facies
Shoreface deposits
Maximum flooding surface
NW
SW
07-27-068-11W6
10.02-067-09W6
11-07-064-04W6
04-08-063-02W6
07-12-061-27W5
10-20-059-25W5
06-12-056-22W5
12-05-054-20W5
10-28-052-18W5
11-09-051-16W5
15-31-048-12W5
15-27-047-07W5
11-07-063-03W5
26.3
50.6
23.4
30.6
20.3
49.9
25.2
25.1
24.3
43.7
54.9
55.7
430
horizontal scale in Km
200 m
160
120
80
40
0
UNIT 4
UNIT 3
UNIT 2
Drumheller c.z.
Basal c.z.
1st flooding surface = Bearpaw MFS
2nd FS
3rd FS
4th FS
5th FS
HORSESHOE CANYON FM.
(EDMONTON GROUP)
BELLY RIVER GROUP
DINOSAUR PARK FM.
OLDMAN FM.

Figure 8



S1
ALBERTA
SASKATCHEWAN
S2
MAASTRICHTIAN
CAMPANIAN
Scollard Formation
Whitemud / Battle formations
unit 5
Horseshoe Canyon Formation
MFS
Drumheller Marine Tongue
D
unit 4
Horseshoe Canyon Formation
Bearpaw Formation
MFS
Wapiti Formation
C
unit 3
Dinosaur Park Formation
B
unit 2
Oldman Formation
Ribstone Creek Mbr.
Lea Park Formation
A
unit 1
Foremost Formation
MFS
Puskwaskau Formation
0 100 200 300 km
0 200 400km
ALBERTA
SASKATCHEWAN
Grande Prairie
Edmonton
BRITISH COLUMBIA
Calgary
U.S.A
U.S.A
N

Figure 9

Paper 4

A high latitude vertebrate fossil assemblage from the Late Cretaceous of West-Central Alberta, Canada: evidence for dinosaur nesting and vertebrate latitudinal gradient

Federico Fanti*[1] and Tetsuto Miyashita[2]

[1] Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Università di Bologna, Via Zamboni 67, 40126 Bologna, Italy

Corresponding author: Tel: +39 051 2094565; Fax: +39 051 2094522;

Email: federico.fanti@unibo.it

[2] Department of Earth and Atmospheric Sciences, University of Alberta, 126 Earth Science Building, Edmonton, Alberta. Canada. T6G 2E3

Running title: A new microfossil locality from the Wapiti Formation

Abstract

This study reports on a new microvertebrate locality from the Campanian (~74 My) fluvial beds of the Wapiti Formation in the Grande Prairie area (west-central Alberta, Canada). This locality represents deposition on a low-gradient, waterlogged alluvial plain approximately 300 km to the north west of the Bearpaw Sea. Detailed sedimentological analyses suggest an environment characterized by an high-sinuosity channel system responsible for widespread oxbow lakes, bogs and marshes. A total of 260 identifiable elements were recovered from three distinct sites at the Kleskun Hill park, documenting a diverse terrestrial and fresh-water palaeocommunity. The recovered fossils include those from hatchling- to nestling-sized hadrosaurid dinosaurs, indicating the presence of a nesting ground in the area. This is the first evidence for dinosaur nesting site in the Wapiti Formation and simultaneously an extremely rare evidence of high-latitude dinosaur nesting, the northernmost in North America to date. A large number of teeth of the small theropod *Troodon* are associated with baby hadrosaurids in the site supporting a northern affinity of this taxon as well as a previously proposed predator-prey association. Other dinosaurs are less common at the locality and include large and small theropods (i.e. tyrannosaurid, *Saurornitholestes*, *Richardoestesia*, *Paronychodon*, and dromaeosaurid) and five ornithischian taxa. Fish, squamate, turtle, and mammal elements were also identified. Collectively, the vertebrate fossil assemblage from the locality allows palaeocommunity reconstruction in the Wapiti Formation. The importance of the data collected from the new locality is twofold: first of all they represent the first comprehensive report from a geographically significant area located between the well-sampled fossil localities of southern Alberta and the high-latitude localities of Alaska. Furthermore, the reconstructed vertebrate fauna support latitudinal gradient of vertebrate distribution along the Western Interior region during the Late Cretaceous.

Keywords: Wapiti Formation, palaeoecology, palaeocommunity, microvertebrate fossil, Campanian, dinosaur nesting.

1. Introduction

Microvertebrate localities from both marine and non-marine deposits are a powerful tool for the study of palaeoecology and palaeobiogeography. They represent a rich source of information on local biota and are useful in addressing a variety of questions in palaeoecology (Sankey 2008a). This study is a preliminary report on a new Campanian microfossil locality from the Wapiti Formation beds exposed at the Kleskun Hill park (Grande Prairie area, north western Alberta, Canada), and the first attempt to document the terrestrial taxa in the formation during the maximum transgression of the Bearpaw Seaway in the Late Cretaceous. High-resolution sedimentological data and an analysis of the heterogeneous fauna were combined to estimate the local biodiversity and the relative abundance of selected groups of vertebrates. In so doing, we focused primarily on faunal composition and comparison, and address implications on environmental factors that characterized the fauna also on the light of the proposed north-south biozonation of vertebrate taxa during the Campanian in western North America (Brinkman, 1990; Eberth, 1990; Brinkman et al., 2004, 2007; Eberth and Brinkman, 1997; Ryan et al., 1998; Fiorillo and Gangloff, 2000; Lehman, 2001; Sankey, 2001, 2008a; Baszio, 2008; Wilson, 2008).

This paper consists of three parts: 1) a detailed description of stratigraphic, sedimentological, and palaeocological signatures at the Kleskun Hill; 2) a statement of the diversity of the vertebrate assemblage recovered; and 3) a discussion on the implication of this locality on latitudinal gradient of vertebrate distribution in the Western Interior during the Late Cretaceous.

2. Geographical and Geological setting

The Kleskun Hill park area is located approximately 25 km northeast of Grande Prairie (north western Alberta) on the left side of the Smoky River (Fig. 1). Discontinuous badlands exposures, the most northern occurrence of this peculiar geomorphology in Alberta (Byrne, 1955), rise up to 100 metres above surrounding plains over an area of 16 km^2. The Kleskun Hill badlands have been considered for years as the richest fossil locality in the Grande Prairie area: hundreds of disarticulated hadrosaur bones and other dinosaur remains collected in the 1940's were referred to an unknown locality within the area (Tanke, 2004). However, to date the locality has been neither mapped nor documented and a description of squamate jaws by Sternberg (1951) is the sole published work on the Kleskun Hill fossils.

The first geological report on the Kleskun Hill was made by Allan and Carr (1946) who tentatively correlated the exposures to the lower Edmonton Formation southeast to the area. However, data from geophysical well logs of exploration boreholes indicate that strata exposed at Kleskun Hill Park lie approximately 340 metres above the base of the Wapiti Formation, within a lithostratigraphic unit characterized by medium to high accommodation conditions, decimetre-to-metre thick bentonitic layers, and well developed, tabular coal seams (Fanti, 2007). This unit is considered an inland equivalent of the Bearpaw shale of central and southern Alberta, rather than that of the lower Edmonton Group (i.e. Horseshoe Formation). Supporting this correlation is a 20 cm thick, olive volcanic ash layer located in the lowermost section of strata exposed in the park (Fig. 2) which yielded an $^{40}Ar/^{39}Ar$ age of 73.77 ± 1.46 My (Eberth, in Fanti, 2007). This age is roughly equivalent to the maximum transgression of the Bearpaw Seaway in central and southern Alberta (*Baculites compressus* zone, 73.4 My; Obradovich, 1993). Therefore, the Kleskun Hill palaeofauna is a rare terrestrial fossil assemblage from a stratigraphic interval represented by marine deposition elsewhere in western Canada and north-western United States. Furthermore, the Wapiti fossil record is geographically important, as the locality is between the deposits of southern Alberta and the high-latitude fossil localities of Alaska (the present day distance is in the range of 400 km north and 3200 km south respectively).

Palaeogeographic reconstruction for the late Campanian of North America place the southern Alberta localities (Belly River Group) at about 58°N palaeolatitude, the Grande Prairie localities at approximately 65°N palaeolatitude (Scotese, 1991; Brinkman, 2003), and the Alaskan localities between 75° and 85°N latitude (Smith and Briden, 1977; Ziegler et al., 1983; Witte et al., 1987). Therefore, in this study the Kleskun Hill park assemblage is referred as high latitude.

3. Materials, methods, and institutional abbreviations

For this study, the Kleskun outcrops were prospected from 2004 to 2008. This led to the identification of three restricted areas where erosive processes and surface hydraulic transportation had concentrated vertebrate remains. These spots will be referred to in the text and figures as Site A, B, and C. Detailed outcrop analyses resulted in a composite cross-section of the study area (S-S', Fig. 2) that permitted to document reciprocal stratigraphic occurrence of fossiliferous sites. Colours used for sedimentological descriptions follow the Munsell Soil Colour Chart.

Following discovery of fossils from the surface of the outcrop, a 4 m^2 area was excavated in 2004 at Site B by the field crew of Royal Tyrrell Museum of Palaeontology (Drumheller, Alberta, Canada). Sandy and silty sediments to the depth of 40 cm were collected for screen washing (sieves of 1 mm). With about 90% of the collected matrix screened and sorted, 29 specimens have been identified. In addition to this, surface collection at Site A, B, and C yielded 231 identifiable specimens (for a total amount of 260 specimens), primarily theropod teeth and hadrosaurid postcranial and teeth fragments.

The collected specimens were primarily identified and compared with those from the well-described Campanian-Maastrichtian vertebrate fossil assemblages in southern Alberta (Brinkman, 1990; Currie et al., 1990; Brinkman and Neuman, 2001; Eberth et al., 2001; Sankey et al., 2002). Identification of hadrosaurid elements, particularly of juvenile and baby-sized individuals, is based on comparisons with *Hypacrosaurus stebingeri* (Horner and Currie, 1994), *Maiasaura peeblesorum* (Horner, 1999), and hadrosauridae indet. from the Horseshoe Canyon (Ryan et al., 1998) and Dinosaur Park formations (Tanke and Brett-Surman, 2001) of Alberta, and the Fruitland Formation (Hall, 1993) of New Mexico. Identification and terminology of the theropod teeth follow Currie et al. (1990), Baszio (1997a), and Fanti and Therrien (2007).

Institutional abbreviation: UALVP, University of Alberta Laboratory of Vertebrate Palaeontology, Edmonton, Alberta, Canada; TMP, Royal Tyrrell Museum of Palaeontology, Drumheller, Alberta, Canada.

Other abbreviations: BW, tooth basal width; FABL, fore-aft basal length; TCH, tooth crown height.

4. Sedimentology

Fluvial deposits exposed at the Kleskun Hill represent a medium-to-high sinuosity channel system within an alluvial plain and comprise predominantly interbedded mudstone, siltstone, and minor sandstone. Sedimentological analyses and facies associations indicate that, overall, the depositional environment was a low-energy, swampy alluvial area where a series of light coloured bentonitic sandstones, organic rich-mudstones, coal seams, thin bentonite, and ironstone beds accumulated under medium to high accommodation conditions (Fig. 2).

The presence of three discrete and laterally persistent coal beds permitted to reliably refer different outcrops and fossiliferous sites to a composite stratigraphic column; significant variations in geometries, lithology, and palaeocurrents within observed inclined heterolitic strata (IHS, *sensu* Thomas et al., 1987) allowed to identify two overlapping intervals in the exposed strata.

The lower interval (zone 1) is characterized by <1-4 metres thick fining-upward sequences of silt and mud with minor fine grained sandstone. Trenches through twelve outcrops show dips of bedding planes between 20° and 35° suggesting a significant component of lateral accretion. IHS consist of brownish silt and grey, organic rich mud forming a graded rhythms within individual inclined units (Fig. 3A). Vertical accretion on top of IHS is documented by oxbow and back swamp deposits that include brown and green mudstones interbedded with wet and immature paleosols, bentonitic horizons, and thin ironstone lenses (Fig. 3B). Gypsy, sideritic, and carbonaceous concretions and nodules are recurrently associated with light coloured sediments of this interval.

Lastly, channel fill deposits of zone 1 are capped by reddish peat horizons, 40 cm thick on average, that gradually change into tabular coal seams up to a metre thick that deep gently westward with an angle of 10-11°. Such layers have been traced at the Kleskun Hill park over an area of approximately 40 km^2 as well as in several well logs in the Grande Prairie region, thus supporting the presence of high-water table and swampy environments over a vast area. Vertebrate remains described herein were primarily recovered from fine, organic-rich deposits of zone 1.

The overlying interval (zone 2) consists of up-to 7 metres thick fining-upward sequences of low angle (5-10°) interbedded sand and silt. Sporadic pebbles and ironstone nodules occur at the base of inclined beds (Fig. 3C). Sandstones are light grey in colour, fine grained, and characterized by a pervasive carbonate cement. Mud component is nearly absent and restricted to discontinuous lenses. Fining-upward deposits are often cut by channel-base fine sands and locally topped by 10-15 cm thick, discontinuous ironstone layers. In spite the fact that silicified plant and wood remains are ubiquitous within this interval, zone 2 lacks organic-rich beds, paleosols, as well as peat and coal, suggesting higher drainage conditions and minor distance from the active channel belt. To date, few and poorly preserved vertebrate remains have been recovered from this interval.

The transition from zone 1 to zone 2 is interpreted as a shift from highly vegetated, swampy and bog-rich environments characterized by permanent high-water table conditions to the active channel belt within the alluvial plain. Differences in lithology and clinoform geometries observed in zone 1 and 2 may also reflect local variations in size, sinuosity, and pattern of the channel system and consequent extension of oxbows and back swamp areas. Palaeocurrent measurements (n=25) taken either parallel or perpendicular to that of clinoforms from both zone 1 and 2 indicate predominant flows direction toward the northeast (average on 25 measurements N60°E). However, a certain degree of variability observed is consistent with a high-sinuosity fluvial system.

Lastly, the top of the exposed interval at the Kleskun Hill is marked by a 35 cm thick, laminated, carbonate cemented sandstone that also denotes the present day prairie level morphology. The subaerial, strongly erosive nature of its basal contact and the coarser grain size of the sandstone suggest a crevasse splay origin.

5. Palaeopedology

The presence in the study area of distinctive paleosol related features provides useful information on soil acidity, precipitations, and water saturation. Pedotype are associated with specific environments (Fastowsky and McSweeney, 1987; Retallack et al., 1987; Retallack, 1994, 2001; Schaetzl and Anderson, 2005) and therefore may provide a reliable way to investigate local environmental and climatic conditions preserved within the Kleskun Hill deposits. Pedotypes features observed in the study area include well developed peat deposits, tabular coal seams, ironstone layers, bentonitic heavily rooted soils, as well as sideritic, calcitic, and gypsic concretions, and discontinuous siliceous/tuffaceous horizons.

The presence of several decimetre-thick peat levels within zone 1 indicate a water-saturated environment with persistent high moisture content, such as bog or fen, characterized by acidic conditions. Peat results from decomposition of significant amount of organic matter (usually plant remains) that accumulated under swamp, marsh, or other kinds of vegetation that can tolerate permanent waterlogged ground (*Histosol*, Retallack, 2001). The presence of extensive vegetation and still water is also indicated by abundant plant remains within the peat layers (including coalified roots, seeds, leaves, and amber), overlaying well developed coal seams, and laminar calcitic concretions generated by flocculation processes. Tabular, decimetre-thick ironstone deposits, also support the presence of widespread bogs in the area and significant amounts of percolating water under tropical or sub-tropical climatic regimes. Acid soil conditions are also responsible for higher Fe concentrations and therefore for the formation of observed sideridic nodules and ironstone layers. The presence of siliceous nodules and tuffaceous concretions within the uppermost portion of channel fill deposits of zone 1, probably reflects intense lisciviation processes of volcanic ash soils over a period of weathering under humid climatic conditions (*Podzols*, Schaetzl and Anderson, 2005). In support of this hypothesis, similar processes observed today are typical of environments characterized by very humid to temperate moist climate, high water table, and associated with coniferous or mixed forests. However, such processes result in light grey coloured horizons deep in the ground, whereas at the Kleskun Hill chert accumulated primarily in concretions that represent casts of roots and cavities. Large, bidimensional (3-5 cm) gypsum crystals and concretions are fairly common within the silty intervals of zone 1 and 2; their abundance suggests paleosol development with possible wet-dry cycles, strongly connected with periods of prolonged subaerial exposure (Retallack, 2001; Schaetzl and Anderson, 2005). However, such crystals are most likely related to digenetic processes influenced by sulphur-rich percolating water and by intense bacterial activity within organic rich bogs (Phillips and Bustin, 1996), as also documented by high sulfur contents within the sediments (more than 600 ppm on average).

6. Vertebrate palaeontology

Dinosaur elements represent nearly 87% (n=225) of the 260 fossils collected from the Kleskun Hill Park and consist predominantly of hadrosaur and theropod teeth (including *Troodon*, tyrannosaurids, *Saurornitholestes*, *Richardoestesia*, *Paronychodon*, dromaeosaurids, and a bird), and hadrosaur postcranial elements (Fig. 4). The remaining specimens include elements from fishes, squamates, turtles, ankylosaurids, ceratopsids, pachycephalosaurids, and mammals, all characteristic components of Campanian terrestrial assemblages in western North America (Ryan et al., 1998; Brinkman, 2008; DeMar and Breithaupt, 2008, and references therein).

6.1. Fish

Three different taxa of fish have been collected from site B, each represented by a single type of element: an esocoid dentary (TMP 2004.23.7), three holostean A scales (TMP 2004.23.6), and a holostean B scale (TMP 2004.23.8; Fig.7). The esocoid dentary has C-shaped tooth bases as in those collected from the Campanian of southern Alberta, and is most similar to *Oldmanesox* sp. in that there are only one or two rows of teeth (Brinkman 1990; Brinkman and Neuman, 2002). As in *Oldmanesox*, the tooth row is single in the posterior part of the dentary (Fig. 7, A-D). The scales of holostean A are identified by a peg-and-socket joint, thin enamel cover, and absence of tab-like extension (Brinkman 1990) (Fig. 7, E-G). The holostean B scale (Fig. H) differs from those of a holostean A in that it has multiple tubercles on the enamelled surface (Brinkman, 1990). The fish elements are virtually indistinguishable from those described from the Campanian of southern Alberta (Brinkman, 1990; Brinkman and Neuman, 2002) (Fig. 7, A-M).

6.2. Non-dinosaurian reptiles

A possible turtle carapace fragment was collected from Site A (Fig. 7), but the weathering on the surface precludes possibility of identifying the element to further taxonomic level.

Squamate remains are relatively abundant and well-preserved in Site A, consisting of articulated skulls and several isolated cranial and postcranial elements. Specimens were recovered exclusively from a discrete bentonitic paleosoil that occurs in the organic-rich deposits of zone 1. Interestingly, squamate remains from the Cretaceous of North America are more commonly found in significantly dryer environments (Gao and Fox, 1991, 1996; Nydam, 2000; Nydam et al., 2007). These noteworthy squamate materials merit detailed systematic description elsewhere and are currently under study.

6.3. Theropoda

6.3.1. Troodontidae

The most abundant theropod teeth recovered from site A are identified as *Troodon* having relatively large, strongly-hooked denticles, and recurved crowns (Fig. 5, A-F). A few specimens have wear facets (Schubert and Ungar, 2005) and spalled surfaces that extend from the apex of the teeth. *Troodon* teeth from the Kleskun Hill park are indistinguishable from other *Troodon* teeth described from deposits of Wyoming (Lance Formation), Montana (Judith River Formation), Alberta (Belly River Group, and Horseshoe Canyon Formation), and Alaska (Prince Creek Formation) (Russell, 1948; Brouwers et al., 1987; Currie, 1987; Currie et al., 1990; Fiorillo and Currie, 1994; Baszio, 1997a; Holtz et al., 1998; Ryan et al., 1998; Sankey et al., 2002, Fiorillo, 2008; Sankey, 2008b). Based on variation in dental morphology along the dental series in *Troodon* (Currie, 1987), the Kleskun Hill specimens encompass the entire tooth series, including premaxillary, posterior maxillary, and posterior dentary teeth. *Troodon* has been reported from other stratigraphic levels and fossil localities of the Wapiti Formation in the Grande Prairie region (Tanke 2004, Currie et al., 2008) supporting a wide distribution of this taxon; however, the relative abundance of *Troodon* teeth is remarkably high at the Kleskun Hill microsites (11.9%).

6.3.2. Dromaeosauridae

Three teeth are identified as *Saurornitholestes* sp. (Fig. 5, H-L) based on elongate and hooked shaped denticles, size differences between anterior and posterior serrations and strong labio-lingual compression (Currie et al., 1990, Baszio, 1997a; Sankey et al., 2002).

6.3.3. Dromaeosauridae indet.

Although only the anterior carina has been preserved, UALVP 50640.01 is distinctive in that denticles vary greatly in size along the crown, from 2.5 to 5 per millimetre, curve slightly distally toward the tip of the tooth, and have sharp ridges of enamel along the midline (Fig. 5, G). Blood grooves (*sensu* Fanti and Therrien, 2007, figure 3B) are absent or restricted to the base of the denticles, being shallow and poorly defined. Both denticles and blood grooves are oriented perpendicular to the longitudinal axis of the tooth. Therefore, specimen UALVP 50640.01 is assigned the taxonomic status Dromaeosauridae indet.

6.3.4. Family unknown

One incomplete tooth (UALVP 48815) is identified as *Paronychodon* sp. (Fig. 5, P). This specimen is the first unequivocal record of this taxon from the Wapiti Formation and is the most northern occurrence to date. The non-serrated tooth has three characteristic longitudinal ridges on both lingual and labial sides, and an elongated and slightly apically curved overall shape (FABL, 2.3 mm; BW, 1.1 mm; TCH, 3.9 mm). The flattened and ridged lingual surface becomes broader anteriorly toward the base of the tooth.

6.3.5. Tyrannosauridae

Fragments of tyrannosaurid teeth are commonly encountered in all the Kleskun Hill microvertebrate fossil sites as well as in other fossil sites in the Grande Prairie area. Denticles are wider labially-lingually than they are long proximodistally and occur 2-2.5 per millimetre in the posterior carina and 3-3.5 per millimetre in the anterior one (Fig. 5, Q-S). Blood grooves are small and restricted to the base of denticles. The most complete tooth (UALVP 48773.2007.6) lacks the basal-most portion and would have exceeded 10 cm in height when complete (FABL, 34.5 mm; BW, 30 mm; TCH 95 mm). The number of denticles per millimetre on the anterior and posterior carinae is 2.5 and 2 respectively. In cross section, the tooth is compressed labio-lingually. It is similar in size and overall morphological characteristics to those of tyrannosaurids from the Campanian and Maastrichtian successions of southern Alberta (Fig. 5, T).

6.3.6. Theropoda incertae sedis

A single small theropod tooth from the site B (TMP 2004.93.3) is assigned to *Richardoestesia gilmorei* based on the minute denticles on the anterior carina and the small denticles on the posterior carina (Currie et al., 1990; Sankey et al., 2002). The tooth lacks the top of the crown, but the morphology is identical to those found in the Campanian deposits of southern Alberta in that it is labiolingually compressed with a moderately recurved posterior carina, and it is relatively small compared to other theropod teeth (Fig. 5, M-O).

6.4. Bird

A small, unserrated tooth from the site B (TMP 2004.93.4) is identified as that of a bird (Fig. 5, U-Z). The tooth is short and lacks denticles, but its posterior margin is blade-like and shows an incipient carina. The crown is more compressed labiolingually than in other theropod teeth from the same locality. It has a few wrinkles on the lingual surface parallel to the anterior margin of the tooth. It also differs from the bird teeth from the Belly River Group (Campanian), southern Alberta described by Sankey et al. (2002) in that the tooth crown recurves slightly posteriorly (Hope, 2002). However, the crown tip is still anterior to the posterior margin of the tooth and the crown base expands anteroposteriorly as in other bird teeth (Sankey et al., 2002).

6.5. Hadrosauridae

More than half of hadrosaurid elements collected at the Kleskun Hill consist of adult-sized teeth and teeth fragments, tendons, and poorly preserved postcranial bones. Teeth are worn on the occlusal surfaces and have a medial carina on the lingual surface.

Other hadrosaurid specimens include three dentary fragments, well preserved teeth, dorsal and caudal centra, a partially preserved pedal phalanx, and an ungual and are all referable to hatchling- to nestling-sized hadrosaurs (Fig. 6). The dentary fragments (Fig. 6, L-Q) have pitted surfaces on both sides, and the alveoli (4-5 mm in width) correspond with size of the teeth. The better preserved baby tooth (UALVP 48748) has a crown height and width of 7 and 4.5 mm respectively, which roughly compares to the largest tooth of an embryonic *Hypacrosaurus stebingeri* (4 mm in width; Horner and Currie, 1994). As in other juvenile hadrosaurid teeth, the tooth is compressed labiolingually relatively to those of a typical hadrosaurid adult. It has the crown-root angle greater than 145 degrees as in lambeosaurines (Horner et al., 2004). The tooth has a straight median carina as in hadrosaurines and some lambeosaurines, and an accessory ridge independent from the median carina on the enameled side as in some lambeosaurine teeth (Horner et al., 2004). Teeth of embryonic or hatchling individuals of *Hypacrosaurus stebingeri* (Horner and Currie, 1994) and Hadrosauridae indet. (Ryan et al., 1998) lack the accessory lingual ridge observed in the Kleskun Hill specimens. Furthermore, the enamel edges have irregular and tiny denticles (*papillae*, after Horner, 1992) toward the apex of the tooth. Other teeth are roughly comparable to UALVP 48748 in size (Fig. 6, A-C).

The baby-sized hadrosaurid vertebrae consist of a single dorsal centrum (UALVP 48816) and four caudal centra (UALVP 48751.01, 48751.02, 50636.03 and 50636.09) (Fig. 6). UALVP 48816 reaches 10 mm in transverse central width, UALVP 48751.01 is 7 mm wide, and UALVP 50636.09 is a distal caudal centrum with 4 mm in width, as wide as the teeth are. All the specimens have smooth sutural surfaces on the dorsal side for the neural arch. The neural canal is relatively broad, being about two thirds of the centrum width. As in other hadrosaurids, immature or mature individuals, the dorsal centrum (UALVP 48816) is hexagonal when viewed anteriorly or posteriorly, and bears ventral keels. The caudal centra (UALVP 48751.01 and 48751.02) are vertically low and transversely wide relative to those of adult hadrosaurids. Ventrally, contact with a haemal arch is not clear. UALVP 48751.01 retains a notochordal pit which has previously been observed for baby hadrosaurid vertebrae from the Horseshoe Canyon Formation (Ryan et al. 1998). The pedal ungual (UALVP 48817; 9 mm in length) is relatively narrow and elongate compared to those in adult hadrosaurids, and is less constricted at the base (Fig. 6, T-U).

The baby hadrosaurid materials from the Kleskun Hill compare well with those of *Hypacrosaurus stebingeri* from the Oldman and Two Medicine formations (Horner and Currie, 1994) and Hadrosauridae indet. from the Horseshoe Canyon Formation (Ryan et al., 1998). The baby-sized hadrosaurid materials are either not worn or with minor abrasion, whereas wear is evident in the adult hadrosaurid elements. The simples assumption is to associate the specimens to a single hadrosaurid taxon. The accessory ridge parallel to the median carina and the relatively large crown-root angle (Horner et al., 2004) further suggest that these are from a lambeosaurine hadrosaur.

6.6.Ceratopsidae

Four ceratopsian teeth were recovered from microsites at the Kleskun Hill park. Three of them (UALVP 50636.08, 50636.10, and 50636.11) are referred to adult individuals based on size, overall shape, and denticulate ridge (Fig. 8, A). Specimen UALVP 50636.08 represents a tooth from a juvenile. It is significantly smaller than other ceratopsian teeth from the locality (FABL, 2 mm; TCH, 3 mm)and is convex in both dorsoventral and mesiodistal views. It contains a sharp, unserrated central ridge as well as less developed secondary ridges and denticles (Fig. 8, B). Ceratopsian remains are often recovered within the fluvial deposits of the Wapiti Formation, usually preserved in large-scale bonebeds. Currently, all identifiable ceratopsian specimens from the formation are referred to two species of *Pachyrhinosaurus* (Tanke, 2004; Fanti and Currie, 2007; Currie et al., 2007, 2008). Therefore the teeth from the Kleskun Hill park are tentatively referred to *Pachyrhinosaurus* sp.

6.7. Ankylosauridae

Two ankylosaurid teeh (UALVP 48747 and TMP 2004.23.9) were recovered from the site A and B respectively. The teeth are weathered to the extent that the enamel surface is almost entirely gone (Fig. 8, C).

6.8. Hypsilophodontidae

A pachycephalosaur tooth (TMP 2004.93.1) were collected from Site B. The base is thickened, and a robust median ridge supports the spade-shape crown with multiple denticles and ridges (Fig. 8, D-G). Tentatively identified as a hypsilophodont, an ornithischian isolated tooth from the site B (TMP 2004.93.5) is heavily worn and weathered. Even though identification of such an incomplete element is difficult, the labiolingually flattened tooth with multiple ridges extending to the base of the crown is most likely a non-hadrosaurid ornithopod. Size of the tooth assumes an animal similar in size with *Parksosaurus* and immature *Thescelosaurus* (Fig. 8, H-L).

6.9. Mammals

Two isolated mammal teeth were collected from site B. One is a multituberculate P^3 (TMP 2004.23.2; Fig. 7, S-T). As in *Chulsanbataar* and others (Clemens and Kielan-Jaworowska, 1978), the premolar is plesiomorphic in having two roots. Its posterolingual part is reduced by anterolingual expansion of the P^4. The four cusps are largely conical and weakly ridged on their anterior and posterior slopes longitudinally. Of the three cusps on the labial side, the anteriormost is the smallest and more lingual than the posterior two. A transversely wide, anteroposteriorly narrow basin sits between the anteriormost labial cusp and the lingual cusp. The second labial cusp is highest, followed by the posteriormost labial cusp and then by the lingual cusp. Based on these characteristics, the premolar most closely resembles that of *Cimolodon*, but the specimen lacks the posterior lingual cusp. In addition, the only lingual cusp is displaced relatively more posteriorly, the anteriormost labial cusp is the smallest, and the posteriormost labial cusp is relatively larger and higher than in previously known species of *Cimolodon*. The tooth is tentatively assigned here to *Cimolodon* sp.

The second specimen is a double-rooted right lower molar of a marsupial, presumably RM_4 (TMP 2004.23.1; Fig. 7, U-Z). The molar is relatively shorter anteroposteriorly than in typical marsupial molars such as that of *Herpeotherium*, and characterized by the trigonid twice as tall as the talonid as in M_4 of *Didelphodon coyi* (Fox and Naylor, 1986). The roots are approximately 1.5 times deeper than height of the trigonid. The molar has styler shelves around its anterior and posterior margins. The metaconid is more anterior than the protoconid, and reduced in size to the shortest cusp in the trigonid. Both the protoconid and paraconid are oriented slightly posteriorly than the metaconid. The triangle formed by the protoconid, metaconid, and paraconid has an acute angle at the protoconid, comparable to *Didelphodon* sp., more acute than *Eodelphis*, and wider than *Didelphodon coyi* (Fox and Naylor, 1986). The talonid basin is slightly narrower transversely than the trigonid, and approximately as long anteroposteriorly as the trigonid. The styler cups A, B, and C are nearly equal in size and form the labial margin of the talonid basin. The styler cusp D is larger, at the posterolabial corner of the talonid. It has two cristae extending toward the hypoconid, and also connects to the posterior styler shelf. The hypoconid is transversely wide, and the prehypoconid crista extends anterolabially, separating a pocket on the lingual side between the protoconid and the hypoconid from the talonid basin. Unlike *Alphadon*, the molar is less than twice anteroposteriorly long as wide across the protoconid (Lillegraven, 1969). Unlike *Pediomys*, the styler cusps sit closer to the trigonid, forming an anteroposteriorly limited talonid basin as in *Didelphodon* (Lillegraven, 1969; Fox and Naylor, 1986). The molar morphology most closely resembles that of *Didelphodon*, and thus it is tentatively referred to *Didelphodon* sp. The molar is about half the size of the previously described *Didelphodon* molars.

7. Discussion

The vertebrate diversity recovered from the Kleskun Hill sites indicates that the locality is a multidominant, high diversity microsite (following the classification and nomenclature proposed by Eberth et al., 2007). The site originated in a channel/overbank-wetland palaeoenvironment characterized by wet and humid climatic conditions. The twelve dinosaur taxa identified outnumber other vertebrates and represent 54.6% of the overall diversity. Hadrosaurid bones and teeth are 46.9% of all the recovered elements and together with theropod teeth (35.4%) constitute the bulk of the collection, with eight taxa represented. Of paramount importance, elements identified as baby and hatchling individuals represent the 18.9% of all hadrosaurian material; these well preserved fossils were subject to negligible pre-burial transportation, strongly supporting the presence of a nesting ground nearby. In addition, the pattern of distribution of different taxa appears to be intimately linked to different depositional environments observed in the Kleskun Hill outcrops. For instance, Site A is characterized by organic-rich clay and mud, and bentonitic paleosols deposited under high- and still-water table conditions suggesting permanent swampy and bogs-like environments. Multidominant microsites are often interpreted as post-deposition reworked assemblages (Brinkman et al., 2007; Eberth et al., 2007; Rogers and Kidwell, 2007). However, sedimentological and palaeontological features observed at Site A suggest accumulation in low-sedimentation-rate palaeoenvironments unaffected by relevant hydraulic transportation or reworking processes (Bown and Kraus, 1981; Eberth et al., 2007). Thus, in terms of depositional system the site is referred to a wetland/bog/marginal-pond palaeoenvironment.

Using the same classification criteria adopted for Site A, sites B and C can be referred to high-diversity multidominant and monodominant microsites respectively (Fig. 9). Site B is dominated by fish remains (37.9%), with frequent theropod (13.8%) and hadrosaur (13.8%) elements, whereas site C is characterized by abundant tyrannosaurs teeth (78.9%). Depositional setting distinguishes site B and C from site A. Both site B and C occur within sandy, well-drained, channel-lag and overbank deposits characterized by high-energy and significant pre-burial reworking and abrasion, as indicated by the poor preservation of vertebrate remains. In addition, elements collected within this interval are: 1) generally larger than those recovered at Site A; and 2) mainly come from large-sized animals (i.e. full grown tyrannosaurs, ceratopsian, and hadrosaurs). Consequently, the taxa represented in those sites are not necessarily representative of the Kleskun Hill park area and may include elements mobilized by hydraulic processes within the active channel belt of the alluvial plain.

7.1 Possible explanation for abundance of Troodon

Hadrosaurids and small theropods (*Troodon*, *Saurornitholestes*, *Paronychodon*, and Dromaeosauridae indet.) represent 76.4% of all the specimens from Site A. Particularly, hatchling- to nestling-sized hadrosaurids occur at 10.9% (baby hadrosaurids account for 17.4% of all hadrosaurian elements), and *Troodon* occupies 16.7%. Ryan et al. (1998) suggested a non-random association between baby hadrosaurids and *Troodon* in a microvertebrate fossil locality in the Horseshoe Canyon Formation of southern Alberta (latest Campanian - early Maastrichtian), where other dinosaur taxa are uncommon. Barring the small sample size of *Troodon* and baby hadrosaurs, their relative abundance may be congruent with Ryan et al.'s finding and possibly expands this distribution of the baby hadrosaurid-*Troodon* association northwards. Ryan et al. (1998) explained the association with the hypothesis that *Troodon* hunted on either young or small sized dinosaurs, at least as a part of their diet. However, the high abundance of both baby hadrosaurids and *Troodon* in Site A alone does not constitute evidence of the predator-prey association in the locality. Whether or not feeding on hatchling and young hadrosaurs, the abundance of small theropods at Site A is probably reflection of relatively large number of small-bodied predators in the area. The small and agile carnivores would have been more successful in a swampy, palustrine, and highly vegetated environment inaccessible to larger carnivores such as tyrannosaurids.

Beside feeding strategy of *Troodon*, the genus seems to show latitudinal gradient in its relative abundance within local theropod faunas. *Troodon* is increasingly more common northward, with 6% occurrence rate in the Judith River Formation of Montana (Currie and Fiorillo, 1994), 31.2% in the northern section of the Wapiti Formation (Fanti, 2007; this paper) and 65% in the Prince Creek Formation of Alaska (Fiorillo and Gangloff, 2000; Fiorillo, 2006). Sankey (2001) rejected the previous assignment of the theropod teeth to *Troodon* sp. from the Aguja Formation of Texas, and suggested that *Troodon* was a member of the northern dinosaur assemblages. The unusual abundance of *Troodon* in the Kleskun Hill locality may not accurately reflect its real abundance in the region because it may assume local environmental factors, such as food source, that favoured assembling *Troodon*. Another confounding problem is that compared localities are not necessarily contemporaneous to each other. Although these caveats suggest that the high *Troodon* occurrence in the north may be partly exaggerated, it is plausible that *Troodon* was more common in northern regions (Baszio, 1997a, b; Fiorillo and Gangloff, 2000).

8. Faunal comparison

In spite of the taxonomical diversity preserved at the Kleskun Hill, the limited sample size precludes a detailed and extensive statistic comparison between the local fauna and fossil association reported elsewhere in western Canada and the United States. However, the microvertebrate fossil assemblage at the Kleskun Hill locality represents 92% of the total vertebrate diversity recovered from the Wapiti Formation to date. For this reason, specimens described in this paper allow a preliminary reconstruction of the palaeocommunity in such an important temporal and geographical context (Fig. 10).

Three fish taxa are recognized from the Kleskun Hill: an esocoid (*Oldmanesox* sp.) and holosteans A and B. They are virtually indistinguishable from their counterparts in the Belly River Group (Campanian) of southern Alberta (Brinkman, 1990; Brinkman and Neuman, 2002) and represent the northernmost record of this association. Holostean A continued to occur into Maastrichtian deposits in southern Alberta (Horseshoe Canyon and Scollard formations, Edmonton Group), although Oldmanesox and holostean B seem to be absent in the Group (Eberth et al., 2001).

Discovery of squamates and a possible turtle from the Kleskun Hill is geographically significant because there has been no report of their occurrence in the high-latitude and polar Late Cretaceous terrestrial localities, including the Prince Creek Formation of Alaska (Buffetaut, 2004; Godefroit et al., 2008). Squamates are also interesting stratigraphically since their post-Bearpaw to early Maastrichtian record is scarce in North America (Gao and Fox,1996). Sternberg (1951) also reported a teiid squamate jaw from the vicinity of the Kleskun Hill park. In addition, Tanke (2004) mentions occurrences of salamander and choristoderan reptiles: however, such specimens were not relocated in any collection and therefore the presence of salamander and choristoderan from the locality are yet to be confirmed.

All the dinosaur taxa are known from the Campanian-Maastrichtian units of southern Alberta (the Belly River Group and Edmonton Group: Brinkman, 1990; Currie et al., 1991) and, except for *Paronychodon*, *Richardoestesia*, and the bird, also from the Prince Creek Formation of Alaska (Rich et al., 1997; Fiorillo and Gangloff, 2000; Gangloff et al., 2003). Notably, the occurrence of *Paronychodon* and *Richardoestesia* are the northernmost records of these enigmatic genera.

Because most taxa are only identified to the higher taxonomic levels (i.e. Tyrannosauridae, Verociraptorinae, Ankylosauridae, Hypsilophodontidae, Lambeosaurinae, Pachycephalosauridae, *Paronychodon*, *Saurornitholestes*, and *Troodon*), it would not be surprising if the dinosaur assemblages in Alaska, northern Alberta, and southern Alberta differed at species or generic level, as predicted by the hypothesis of dinosaur provincialism in western North America during the Campanian and Maastrichtian (Lehman, 2001). The current data from the Wapiti Formation support a wide distribution of all dinosaur families and subfamilies discussed in this paper along the Western Interior during the Campanian and Maastrichtian, although this does not necessarily refute the hypothesis of provincialism.

The mammals are tentatively identified as *Cimolodon* sp. and *Didelphodon* sp. respectively and are the northernmost occurrence for the genera. In particular, *Didelphodon* sp. from the Kleskun Hill is most similar to *Didelphodon* sp. from the Scabby Bute of southern Alberta (St. Mary River Formation, Edmonton Group: Fox and Naylor, 1986) based on the acute triangle formed by the trigonid cusps, suggesting a close phylogenetic relationship. Discovery of both a multituberculate and a marsupial is not surprising, because these mammals were already reported from Alberta (Lillegraven, 1969; Fox, 2005) and from the Prince Creek Formation (Santonian-Maastrichtian) of Alaska (Clemens and Nels, 1993; Fiorillo and Gangloff, 2000). Pending taxonomic assignment of the Alaskan fossils, the Kleskun Hill specimens are potentially important for mammal palaeobiogeography during the Late Cretaceous of North America.

According to the most recently compiled dinosaur and other vertebrate faunal lists (Tanke, 1988, 2004; Currie, 1989a; Ryan and Russell, 2001; Weishampel et al. 2004) and in the light of recent dinosaur discoveries in the Grande Prairie area (Fanti and Currie, 2007; Currie et al., 2008; this paper) more than thirty-five species are currently known from the Wapiti Formation. Amongst these taxa, the ceratopsian dinosaur *Pachyrhinosaurus lakustai* (Currie et al., 2008) is the only diagnostic vertebrate taxon described from the formation. Currie et al. (2008) also confirmed that a second ceratopsian bonebed above the Campanian-Maastrichtian boundary in the Wapiti Formation yielded a chelydrid turtle neural plate, a varanid squamate vertebra, and crocodile scutes.

9. Nesting of Hadrosaurids

Hatchling- to nestling-sized hadrosaurid elements from the Kleskun Hill park indicate that hadrosaurids nested in the area in the late Campanian (~74 My). An high-latitude record of dinosaur nesting is extremely rare. Recently, Godefroit et al. (2008) reported eggshell fragments and juvenile hadrosaur elements from a latest Cretaceous locality in northern Siberia. In North America, G. Nelms, in Carpenter (1999) mentions "*Edmontosaurus* sp. bones" from the Prince Creek Formation of Ocean Point, Alaska, in the global survey of baby dinosaur records. However, the supposed Alaskan baby *Edmontosaurus* has neither been described nor illustrated since Nelm's personal communication to Carpenter (1999). In addition, the presence of *Edmontosaurus* is yet to be confirmed from Alaska (Bell and Snively, 2008). Therefore, the report on the Alaskan baby dinosaur material is considered not reliable in this study. The Kleskun Hill locality is currently the northernmost published record of a dinosaur nesting ground in North America, pending proper assessment of the Alaskan material.

The hypothesized hadrosaurid nesting site at the Kleskun Hill is also important in a palaeoecological perspective. Previously, hadrosaurid nesting sites (referring to localities where eggshells or embryonic elements have been reported) seemed to preferentially occur in dry, upland regions (Horner 1982; Horner and Currie 1994). Carpenter (1982; 1992), and Fiorillo (1987; 1989) reported eggshells and baby or juvenile hadrosaurid specimens from the low-land settings (the Lance and Hell Creek formations and the Judith River Formation, respectively). In Alberta, Nadon (1993) noted common occurrence of eggshells from the anastomosed fluvial deposits of the St. Mary River Formation, Ryan et al. (1998) described hatchiling- to nestling-sized hadrosaurid elements from the Horseshoe Canyon Formation, and Tanke and Brett-Surman (2001) also reported hatchling- to nestling-sized hadrosaurid elements and eggshells from the low-land Dinosaur Park Formation of southern Alberta. Coupled with these previous findings, the Kleskun Hill hadrosaurid materials provide further evidences that hadrosaurids also nested in low-land settings. Nadon (1993) proposed that ornithopods preferentially selected wetland habitats as ideal reproductive site where a soft substrate and flooded conditions would have deterred large carnivores. The implications are that hadrosaurids seem to have had various strategies in nesting site selection, and that the fossil record of nesting sites is taphonomically biased against wet, lowland environment as weak acidity in groundwater would have generally enhanced dissolution of eggshells and poorly ossified elements unless buffered.

In addition to hadrosaurids, small ceratopsian elements imply that ceratopsians either nested in the region or had not migrated over long distance from the nesting site (Currie, 1989b; Clemens and Nelms, 1993; Fiorillo and Gangloff, 2001). Interestingly, postcranial elements ascribed to juvenile and subadult hadrosaurs have been collected from nearly coeval strata cropping out along the Wapiti River south of Grande Prairie (see also Tanke, 2004). Furthermore, Currie et al. (2008) report of an almost complete ontogenetic serie of *Pachyrhinosaurus lakustai* (including juvenile, subadult, and adult individual) from the densely packed Pipestone Creek bone bed which has been dated 73.27 ± 0.25 My. Palaeogegraphic reconstruction for the Bearpaw time (Dawson et al., 1994) place the Grande Prairie area in the order of 250-300 kilometres from the shoreline, located approximately to the north and to the west of Edmonton. Sedimentological data and palaeoenvironmental reconstruction presented in this study support an extensive low-land environment (referring to the low and relatively level ground of the region, in contrast with adjacent higher country), genetically related to the maximum transgressive phase of the Bearpaw Sea

10. Conclusion

The Kleskun Hill park vertebrate fauna represents the first high-diversity multidominant assemblage from the Late Cretaceous of north western Canada. The fauna is also stratigraphically important being the only locality that provides a glimpse of a diverse terrestrial vertebrate fauna in western North America during the Bearpaw Sea transgressive event about 74 My. At the Kleskun Hill Park, site A best represents the vertebrate diversity of the formation because of the larger sample size. The site is characterized by relative abundance of *Troodon* teeth and hatchling- to nestling-sized hadrosaur elements. The latter suggests the presence of an hadrosaurid nesting ground in the nearby lowland area within the alluvial plain. In contrast sites B and C, both with a smaller sample size, preserve a reworked assemblage dominated by pre-burial fluvial transportation. The Kleskun Hill vertebrate fauna preserves many taxa that are common in Campanian terrestrial vertebrate faunas in southern Alberta. The locality marks the northernmost distribution of *Paronychodon* and *Richardoestesia*. Additionally, three fish taxa (holosteans A and B, and an escoid *Oldmanesox* sp.), squamates, and bird have not been reported from Alaska to date. Multituberculates and marsupials have been reported from the Prince Creek Formation of Alaska (Clemens and Nels, 1993), but it is not clear if the Kleskun Hill Park taxa (*Cimolodon* sp. and *Didelphodon* sp.) are identical to their counterparts in the Campanian of southern Alberta and Alaska. An impeding task is more sampling at the Kleskun Hill and assessment of new material from the Alaskan localities which may further result in testing the hypothesis of dinosaur provinciality (Lehman, 2001). Although the sample size remains small, the preliminary account of the vertebrate diversity demonstrates that the Grande Prairie region promise to be a key area in both stratigraphic and palaeobiogeographic contexts during the Late Cretaceous of North America.

Acknowledgements

We thank the Palaeontological Society of Peace, especially Sheldon Graber, Robert Hunt, Katalin Ormay, Desh Mittra, and their families, the Grande Prairie Regional College, Philip Currie and Eva Koppelhus (University of Alberta, Edmonton) for logistic supports in field. Many thanks are also extended to Nick Ormay and Walter Paszkowski for their contribution to fieldwork. Don Brinkman (TMP) and Patty Ralrick did initial sorting and identification of the specimens stored in TMP. F.F. is also indebted to Dennis Braman, Donald Brinkman, and David Eberth (TMP) for sharing unpublished data and for stimulating discussions. Don Brinkman, James Gardner, Brandon Strilisky (TMP) and Philip Currie (U. of A.) provided access to the collections in their care. Comments from Julia Sankey (California State University Stanislaus, Turlock, USA), Finn Surlyk (Kobenhavn Universited, Denmark), and anonymous reviewer greatly improved this manuscript. The first draft benefited from discussion with Paul McNeil (Grande Prairie Regional College) and Darren Tanke (TMP). We also acknowledge Philip Currie, Eva Koppelhus, Rich Palmer (University of Alberta), Don Henderson (TMP), and Kesia Andressen for their support at various stages of the project. The specimens were illustrated by Lukas Panzarin. T.M. extends thanks to students and staffs at Ohwada Primary School of Hachioji (1992-1998) for continuing encouragements. This work was supported by the University of Bologna, Museum of Geology and Palaeontology Giovanni Capellini (Bologna, Italy), Jurassic Foundation, Dinosaur Research Institute, and Grande Prairie Regional College to F.F., and by personal funds from Junichi and Kanae Miyashita to T.M.

References

Allan, J., Carr, J., 1946. Geology and Coal Occurrences of Wapiti-Cutbank Area, Alberta. Research Council of Alberta Report 48, 50 pp.

Baszio, S., 1997a. Systematic palaeontology of isolated dinosaur teeth from the Latest Cretaceous of South Alberta, Canada. Courier Forschungsinstitut Senckenberg 196, 33–77.

Baszio, S., 1997b. Palaeoecology of dinosaur assemblages throughout the Late Cretaceous of South Alberta, Canada. Courier Forschungsinstitut Senckenberg 196, 1–31.

Baszio, S., 2008. Information from microvertebrate sites, sampling, statistical methods, and taphonomy. In: Sankey, J., Baszio, S. (Eds.), Vertebrate microfossil assemblages. Indiana University Press, Bloomington and Indianapolis, pp. 3–8.

Bell, P., Snively, E. 2008. Polar dinosaurs on parade: a review of dinosaur migration. Alcheringa 32, 271–284.

Bown, T., Kraus, M., 1981. Vertebrate fossil-bearing paleosol units (Willwood Formation, Lower Eocene, Northwest Wyoming, U.S.): applications for taphonomy, biostratigraphy, and assemblage analysis. Palaeogeography, Palaeoclimatology, Palaeoecology 34, 31–56.

Brinkman, D., 1990. Paleoecology of the Judih River Formation (Campanian) of Dinosaur Provincial Park, Alberta, Canada: evidence from vertebrate microfossil localities. Palaeogeography, Palaeoclimatology, Palaeoecology 78, 37–54.

Brinkman, D., 2003. A review of nonmarine turtles from the late Cretaceous of Alberta. Canadian Journal of Earth Sciences 40, 557–571.

Brinkman, D., 2008. The structure of Late Cretaceous (Late Campanian) nonmarine aquatic communities: a guild analysis of two vertebrate microfossil localities in Dinosaur Provincial Park, Alberta, Canada. In: Sankey, J., Baszio, S. (Eds.), Vertebrate microfossil assemblages. Indiana University Press, Bloomington and Indianapolis, pp. 33–60.

Brinkman, D., Neuman, A. 2002. Teleost centra from Uppermost Judith River Group (Dinosaur Park Formation, Campanian) of Alberta, Canada. Journal of Paleontology 76, 138–155.

Brinkman, D., Russell, A., Eberth, D., Peng, J., 2004. Vertebrate palaeocommunities of the lower Judith River Group (Campanian) of southeastern Alberta, Canada, as interpreted from vertebrate microfossil assemblages. Palaeogeography, Palaeoclimatology, Palaeoecology 213, 295–313.

Brinkman, D., Eberth, D., Currie, P., 2007. From bonebeds to paleobiology: applications of bonebed data. In: Rogers, R., Eberth, D., Fiorillo, A. (Eds.) Bonebed: genesis, analysis, and paleobiological significance. The University of Chicago Press, Chicago and London, pp. 221–263.

Brouwers, E., Clemens, W., Spicer, R., Ager, T., Carter, D., and Sliter, W., 1987. Dinosaurs on the North Slope, Alaska: High Latitude, Latest Cretaceous Environments. Science 237, 1608–1610.

Buffetaut, E., 2004. Polar dinosaurs and the question of dinosaur extinction: a brief review. Palaeogeography, Palaeoclimatology, Palaeoecology 214, 225–231.

Byrne, P., 1955. Bentonite in Alberta. Research Council of Alberta Report 71, 20 pp.

Carpenter, K., 1982. Baby dinosaurs from the Late Cretaceous Lance and Hell Creek formations and a description of a new species of theropod. Contributions to Geology (University of Wyoming) 20, 123–134.

Carpenter, K., 1992. Behavior of hadrosaurs as interpreted from footprints in the "Mesaverde" Group (Campanian) of Colorado, Utah, and Wyoming. Contributions to Geology (University of Wyoming) 29, 81–96.

Carpenter, K. 1999. Eggs, Nests, and Baby Dinosaurs. Indiana University Press, Bloomington. 336 pp.

Clemens, W., Kielan-Jaworowska, Z., 1978. Multituberculates. In: Lillegraven, J., Kielan-Jaworowska, Z., Clemens, W. (Eds.), Mesozoic Mammals, the first two thirds of mammalian history. University of California Press, Berkeley, pp. 99–149.

Clemens, W., Nelms, G., 1993. Paleoecological implications of Alaskan terrestrial vertebrate fauna in latest Cretaceous time at high paleolatitudes. Geology 21, 503–506.

Cope, E., 1876. Descriptions of some vertebrate remains from the Fort Union beds of Montana. Philadelphia Academy of Natural Sciences, Proceedings 1876, 248–261.

Currie, P., 1989a. Dinosaur footprints of western Canada. In: Gillette, D., Lockley, M. (Eds.), Dinosaur track and traces. Cambridge University Press, Cambridge, pp. 293–300.

Currie, P., 1989b. Long-distance dinosaurs. Natural History 6, 60–65

Currie, P., Rigby, J., Sloan, R., 1990. Theropod teeth from the Judith River Formation of southern Alberta, Canada. In: Currie, P., Carpenter, K. (Eds.), Dinosaur Systematics: approaches and perspectives. Cambridge University Press, Cambridge, pp. 107–125.

Currie, P., Langston, W., Tanke, D., 2007. A new Pachyrhinosaur from the Wapiti Formation of Grande Prairie, Alberta. In: Braman, D. (Ed.), Ceratopsian Symposium, Short Papers, Abstracts, and Programs, pp. 22.

Currie, P., Langston, W., Tanke, D. 2008. A New Horned Dinosaur from an Upper Cretaceous Bonebed in Alberta. National Engineering Council Research Press, Ottawa. 152 pp.

Dawson, F., Evans, C., Marsh, R., and Richardson, R. 1994: Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin. In: Mossop G., Shetson, I. (Eds.), Geological Atlas of the Western Canada Sedimentary Basin. Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, Chapter. 24, 18 pp.

DeMar, D., Breithaupt, B., 2008. Terrestrial and aquatic vertebrate paleocommunities of the mesaverde formation (Upper Cretaceous, Campanian) of the Milk River and Bighorn Basins, Wyoming, USA. In: Sankey, J., Baszio, S. (Eds.), Vertebrate microfossil assemblages. Indiana University Press, Bloomington and Indianapolis, pp. 78–103.

Eberth, D., 1990. Stratigraphy and sedimentology of vertebrate microfossil sites in the uppermost Judith River Formation (Campanian), Dinosaur Provincial Park, Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 78, 1–36.

Eberth, D., Brinkman, D., 1997. Paleoecology of an estuarine, incised-valley fill in the Dinosaur Park Formation (Judith River Group, Upper Cretaceous) of southern Alberta, Canada. Palaios 12, 43–58.

Eberth, D., Currie, P., Brinkman, D., Ryan, M., Braman, D., Gardner, J., Lam, V., Spivak, D., Neuman, A. 2001. Alberta's dinosaurs and other fossil vertebrates: Judith River and Edmonton groups (Campanian - Maastrichtian). In: Hill, C. (Ed.) Guidebook for the Field Trips: Mesozoic and Cenoxoic Paleontology in the western plains and Rocky Mountains. Museum of the Rockies Occasional Paper 3, 47–75.

Eberth, D., Shannon, M., Noland, B., 2007. A bonebed database: classification, biases, and pattern of occurrence. In: Rogers, R., Eberth, D., Fiorillo, A. (Eds.) Bonebed: genesis, analysis, and paleobiological significance. The University of Chicago Press, Chicago and London, pp. 103–219.

Fanti, F., 2007. Unfolding the geological history of the North: new comprehensive survey of the Wapiti Formation, Alberta, Canada. In: Braman, D. (Ed.) Ceratopsian Symposium, Short Papers, Abstracts and Programs, 33–38.

Fanti, F., Currie, P., 2007. A new Pachyrhinosurus bonebed from the late Cretaceous Wapiti Formation. In: Braman, D. (Ed.), Ceratopsian Symposium, Short Papers, Abstracts, and Programs, pp. 39–43.

Fanti, F., Therrien, F., 2007. Theropod tooth assemblages from the Late Cretaceous Maevarano Formation and the possible presence of dromaeosaurids in Madagascar. Acta Palaeontologica Polonica 52, 155–166.

Fastovsky, D., McSweeney, K., 1987. Paleosols spanning the Cretaceous-Paleogene transition, eastern Montana and western North Dakota. Palaios 2, 282–295.

Fiorillo, A., 1987. Significance of juvenile dinosaurs from Careless Creek Quarry (Judith River Formation), Wheatland County, Montana. In: Currie, P., Koster, E. (Eds.) Fourth Symposium on Mesoxoinc Terrestrial Ecosystems: short papers. Royal Tyrrell Museum of Palaeontology Occasional Paper 3, pp.89–95.

Fiorillo, A., 1989. The vertebrate fauna from the Judith River Formation (Late Cretaceous) of Wheatland and Golden Valley Counties, Montana. Mosasaur 4, 127–142.

Fiorillo, A., 2006. Review of the dinosaur record of Alaska with comments regarding Korean dinosaurs as comparable high-latitude fossil faunas. Journal of Paleontological Society of Korea 22, 15–27.

Fiorillo, A., 2008. On the occurrence of exceptionally large teeth of *Troodon* (Dinosauria: Saurischia) from the Late Cretaceous of northern Alaska. Palaios 23, 322–328.

Fiorillo, A., Currie, P., 1994. Theropod teeth from the Judith River Formation (Upper Cretaceous) of south-central Montana. Journal of Vertebrate Paleontology 14, 74–80.

Fiorillo, A., Gangloff, R., 2000. Theropod teeth from the Prince Creek Formation (Cretaceous) of northern Alaska, with speculation on artic dinosaur paleoecology. Journal of Vertebrate Paleontology 20, 675–682.

Fiorillo, A., Parrish, J., 2004. The first record of a Cretaceous dinosaur from Alaska. Cretaceous Research 25, 453–458.

Fiorillo, A., McCarthy, P., Brandlen, E., Flaig, P., Norton, D., Jacobs, L., Zippi, P., Gangloff, R., 2007. Paleontology, sedimentology, paleopedology, and palynology of the Kikak-Tegoseak Quarry (Prince Creek Formation: Late Cretaceous), northern Alaska. In: Braman, D. (Ed.), Ceratopsian Symposium, Short Papers, Abstracts, and Programs, pp. 48–51.

Fox, R., Naylor, B., 1986. A new species of *Didelphodon* Mash (Marsupialia) from the Upper Cretaceous of Alberta, Canada: paleobiology and phylogeny. Neues Jahrbuch fur Geologie unde Palaontologie, Abhandlungen 172, 357–380.

Gao, K., Fox, R., 1991. New teiids lizards from the Upper Cretaceous Oldman Formation (Judithian) of southwestern Alberta, Canada, with a review of the Cretaceous record of teiids. Annals of the Carnegie Museum 60, 145–162.

Gao, K., Fox, R., 1996. Taxonomy and evolution of Late Cretaceous lizards (Reptilia:Squamata) from western Canada. Bulletin of the Carnegie Museum of Natural History 33, 1–107.

Godefroit, P., Golovneva, L., Schepetov, S., Garcia, G., Alekseev, P.,2008. The last polar dinosaurs: high diversity of la test Cretaceous arctic dinosaur in Russia. Naturwissenschaften. Published online: December 2008, 7 pp.

Hall, J., 1993. A juvenile hadrosaurid from New Mexico. Journal of Vertebrate Paleontology 13, 367–369.

Hope, S., 2002. The Mesozoic radiation of Neornithes. In: Chiappe, L., Witmer, L. (Eds.), Mesozoic birds: above the heads of dinosaurs. University of California Press, Berkley, pp. 339–388.

Horner, J., 1982. Evidence for colonial nesting and "site fidelity" among ornithischian dinosaurs. Nature 297, 675–676.

Horner, J., 1999. Egg clutches and embryos of two hadrosaurian dinosaurs. Journal of Vertebrate Paleontology 19, 607–611.

Horner, J., Currie, P., 1994. Embryonic and neonatal morphology and ontogeny of a new species of *Hypacrosaurus* (Ornithiscia, Lambeosauridae) from Montana and Alberta. In: Carperter, K., Hirsch, K., Horner, J. (Eds.), Dinosaur Eggs and Babies. Cambridge University Press, New York, pp. 310–356.

Horner, J., Weishampel, D., Forster, C., 2004. Hadrosauridae. In: Weishampel, D., Dodson, P., Osmolska, H. (Eds.) The Dinosauria (2nd edition). University of California Press, Berkeley, pp. 438–463.

Jamniczky, H., Brinkman, D., Russell., A., 2008. How much is enough? A repeatable, efficient, and controlled sampling protocol fro assessing taxonomic diversity and abundance in vertebrate microfossil assemblages. In: Sankey, J., Baszio, S. (Eds.), Vertebrate microfossil assemblages. Indiana University Press, Bloomington and Indianapolis, pp.9–16.

Lehman, T., 1987. Late Maastrichtian paleoenvironments and dinosaur biogeography in the Western Interior of North America. Palaeogeography, Palaeoclimatology, Palaeoecology 60, 189–217.

Lehman, T., 1997. Late Campanian dinosaur biogeography in the western interior of North America. In: Wolberg, D., Stump, E., Rosenberg, G. (Eds.), Dinofest International. Academy of Natural Sciences, Philadelphia, pp. 223–240.

Lehman, T., 2001. Late Cretaceous dinosaur Provinciality. In: Tanke, D., Carpenter, K. (Eds.), Mesozoic Vertebrate Life. Indiana University Press, pp. 310–328.

Leidy, J., 1856. Notices of remains of extinct reptiles and fishes discovered by Dr. F.V. Hayden in the Bad Lands of the Judith River, Nebraska Territory, Philadelphia Academy of Natural Sciences, Proceedings, 72–73.

Lillegraven, J., 1969. Latest Cretaceous mammals of upper part of Edmonton Formation of Alberta, Canada, and review of marsupial-placental dichotomy in mammalian evolution. The University of Kansas Paleontological Contributions 50, 1–122.

Nadon, G., 1993. The association of anastomosed fluvial deposits and dinosaur tracks, eggs, and nests. Implications for the interpretation of floodplain environments and a possible survival strategy for ornithopods. Palaios 8, 31–44.

Nydam, R., 2000. A new taxon of helodermatid-like lizard from the Albian-Cenomanian of Utah. Journal of Vertebrate Paleontology 20, 285–294.

Nydam, R., Eaton, J., and Sankey, J.,2007. New taxa of transversely-toothed lizards (Squamata:Scincomorpha) and new information on the evolutionary history of "Teiids". Journal of Vertebrate Paleontology 81, 538–549.

Obradovich, J., 1993. A Cretaceous time-scale. In: Caldwell, W., Kauffman, E. (Eds.), Evolution of the Western Interior Basin. Geological Association of Canada Special Paper 39, pp. 379–396.

Parrish, J.M., Parrish, J.T., Hutchison, J., Spicer, R., 1987. Late Cretaceous vertebrate fossils from the North Slope of Alaska and implications for dinosaur ecology. Palaios 2, 377–389.

Phillips, S., Bustin, M., 1996. Sulfur in the Changuinola peat deposits, Panama, as an indicator of the environments of deposition of peat and coal. Journal of Sedimentary Research 66, 184–196.

Retallack, G., 1994. A pedotype approach to latest Cretaceous and earliest Tertiary paleosols in eastern Montana. Geological Society of America Bulletin 106, 1377-1397.

Retallack, G., 2001. Soils of the past – an introduction to paleopedology. Blackwell Science, New York, USA, 404 pp.

Retallack, G., Leahy, G., Spoon, M., 1987. Evidence from paleosols for ecosystem changes across the Cretaceous/Tertiary boundary in eastern Montana. Geology 15, 1090–1093.

Rogers, R., Kidwell, S., 2007. A conceptual framework for the genesis and analysis of vertebrate skeletal concentrations. In: Rogers, R., Eberth, D., Fiorillo, A. (Eds.) Bonebed: genesis, analysis, and paleobiological significance. The University of Chicago Press, Chicago and London, pp. 1–63.

Russell, L. 1948. The dentary of *Troodon*, a genus of theropod dinosaurs. Journal of Paleontology, 22, 625–629.

Ryan, M., Currie, P., Gardner, J., Vickaryous, M., Lavigne, J., 1998. Baby hadrosaurid material

Associate with unusually high abundance of *Troodon* teeth from the Horseshoe Canyon formation, Upper Cretaceous, Alberta, Canada. Gaia, 15, 123–133.

Ryan, M., Russell, A., 2001. Dinosaurs of Alberta (exclusive of Aves). In: Tanke, D., Carpenter, K. (Eds.), Mesozoic Vertebrate Life. Indiana University Press, Bloomington, pp. 279–297.

Sampson, S., Lowen, M., 2007. New information on the diversity, stratigraphic distribution, biogeography, and evolution of ceratopsid dinosaurs. In: Braman, D. (Ed.), Ceratopsian Symposium, Short Papers, Abstracts, and Programs, pp. 125–133.

Sankey, J., 2001. Late Campanian southern dinosaurs, Aguja Formation, Big Bend, Texas. Journal of Paleontology 75, 208–215.

Sankey, J., 2008a. Vertebrate paleoecology from microsites, Talley mountain, Upper Aguja Formation (Late Cretaceous), Big Bend National Park, Texas, USA. In: Sankey, J., Baszio, S. (Eds.), Vertebrate microfossil assemblages. Indiana University Press, Bloomington and Indianapolis, pp. 61–77.

Sankey, J., 2008b. Diversity of latest Cretaceous (Late Maastrichtian) small theropods and birds: teeth from the Lance and Hell Creek formations, USA. In: Sankey, J., Baszio, S. (Eds.), Vertebrate Microfossil Assemblages. Indiana University Press, pp. 117–134.

Sankey, J., Brinkman, D., Guenther, M., Currie, P., 2002. Small theropod and bird teeth from the Late Cretaceous (Late Campanian) Judith River Group, Alberta. Journal of Paleontology 76, 751–763.

Schaetzl, R., Anderson, S., 2005. Soils, genesis and geomorphology. Cambridge University Press, New York, 838 pp.

Schubert, B., Ungar, P., 2005. Wear facets and enamel spalling in tyrannosaurid dinosaurs. Acta Palaeontologica Polonica 50, 93–99.

Scotese, C., 1991. Jurassic and Cretaceous plate tectonic reconstruction. Palaeogeography, Palaeoclimatology, Palaeoecology 87, 493–501.

Smith, A., Briden, J, 1977. Mesozoic and Cenozoic paleocontinental maps. Cambridge University Press, Cambridge, 63 pp.

Sternberg, C., 1951. The lizard *Chamops* from the Wapiti Formation of northern Alberta: *Polyodontosaurus grandis* is not a lizard. Bulletin of the National Museum of Canada 123, 256–258.

Tanke, D., 1988. Ontogeny and dimorphism in Pachyrhinosaurus (Reptilia, Ceratopsidae), Pipestone Creek, N. W. Alberta, Canada. Journal of Vertebrate Paleontology 8, 27A.

Tanke, D., 2004. Mosquitoes and mud. The 2003 Royal Tyrrell Museum of Paleontology expedition to the Grande Prairie region (north-western Alberta, Canada). Alberta Paleontological Society Bulletin 19, 3–31.

Tanke, D., Brett-Surman, M., 2001. Evidence of hatchling- and nesting-size hadrosaur (Reptilia: Ornithischia) from Dinosaur Provincial Park (Dinosaur Park Formation: Campanian), Alberta. In: Tanke, D., Carpenter, K. (Eds.), Mesozoic Vertebrate Life. Indiana University Press, pp. 206–218.

Weishampel, D., Barrett, P., Coria, R., Loeuff, J., Xu, X., Zhao, X., Sahni, A., Gomani, E., Noto, C., 2004. Dinosaur distribution. In: Weishampel, D., Dodson, P., Osmolska, H. (Eds.), The Dinosauria (2nd edition). University of California Press, Berkeley, pp. 517–606.

Wilson, L., 2008. Comparative taphonomy and paleoecological reconstruction of two microvertebrate accumulations from the Late Cretaceous Hell Creek Formation (Maastrichtian), eastern Montana. Palaios 23, 289–297.

Witte, K., Stone, D., Mull, C., 1987. Paleomagnetism, paleobotany, and paleogeography of the Cretaceous, North Slope, Alaska. In: Tailleur, I., Weimer, P. (Eds.), Alaska North Slope geology. The Pacific Section, Bakersfield, Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, Volume 1, pp. 571–579.

Ziegler, A., Scotese, C., Barrett, S., 1983. Mesozoic and Cenozoic paleogeographic maps. In: Brosche, P., Sundermann, J. (Eds.), Tidal friction and the Earth's rotation, II. Springer Verlag, Berlin, pp. 240–252.

Figure captions

Fig. 1. **A**, reference map of Alberta (Canada) showing the extension of the Campanian-Maastrichtian Wapiti Formation. **B**, location of the study area northeast of Grande Prairie. Sites A, B, and C are located within the Kleskun Hill park area. Contour lines elevation data are expressed in metres. S-S', cross section shown in Figure 2.

Fig. 2. Composite stratigraphic section showing the stratigraphic occurrence of sites A, B, and C as well as the only dated bentonite from the Kleskun Hill locality. Paleocurrent directions are represented by rose diagrams close to the beds in which the sedimentary structures were observed.

Fig. 3. Exposures of the Campanian fluvial deposits of the Wapiti Formation at the Kleskun Hill

Park. **A**, interbedded light coloured silt and organich-rich mudstones (IHS) capped by a couplet of tabular reddish peat and coal. **B**, heavily rooted paleosol formed by interbedded dark grey, organic-rich mudstone and whitish, carbonaceous mudstone overlying a 45 cm thick coal bed. **C**, the transition from muddy, organic-rich deposits of zone 1 to overlying silty and sandy channel facies of zone 2 (see text for discussion). **D**, site A. **E**, site B. **F**, site C (see also Figure 1).

Fig. 4. Microvertebrate specimens (n=260) from the Kleskun Hill locality, Wapiti Formation. Dinosaur elements comprise the 86.5% of recovered elements (particularly hadrosaurid and theropod elements), and squamates and fishes are largely represented.

Fig. 5. Miscellaneous theropod and bird teeth from Kleskun Hill Park, Grande Prairie, Alberta. **A-B**, *Troodon* posterior premaxillary or anterior maxillary tooth (TMP 2004.23.3): **A**, detail of posterior denticles; **B**, entire specimen (lingual and labial). **C**, *Troodon* posterior dentary tooth, UALVP 48750 (labial and lingual); **D-E**, *Troodon* premaxillary tooth, UALVP 48755 (labial): **D**, detail of denticles; **C**-entire specimen. **F**, *Troodon*, UALVP 48753, anterior maxillary tooth (lingual and labial). **G**, Dromaeosauridae indet. tooth, detail of the posterior carina, UALVP 50640.01. **H-L**, *Saurornitholestes* tooth, TMP 2004.23.4: **H**, detail of posterior denticles; **I**, entire specimen (labial and lingual); **L**, detail of anterior denticles. **M-O**, *Richardoestesia* tooth, TMP 2004.93.3: **M**, detail of posterior denticles; **N**, entire specimen; **O**, detail of anterior denticles. **P**, *Paronychodon* tooth, UALVP 48815 (labial and lingual). **Q**, Tyrannosauroid tooth, UALVP 50641.01 (anterior). **R**, Tyrannosauroid tooth, UALVP 48760, detail of denticles. **S**, Tyrannosauroid premaxillary tooth, UALVP 50641.02 (lingual). **T**, Tyrannosauroid tooth, (?dentary), UALVP 48773 (labial and lingual). **U-Z**, bird tooth, TMP 2004.93.4: **U**, basal section; **V-Z**, entire specimen (lingual and labial).

Fig. 6. Baby and juvenile hadrosaurid elements from Kleskun Hill Park, Grande Prairie, Alberta. **A-C**, baby teeth (lingual): **A**, UALVP 50636.01, **B**, UALVP 48748, **C**, UALVP 50636.02. **D**, dorsal centrum, UALVP 48816. **E**, caudal centrum, UALVP 50636.03. **F-H**, caudal centrum, UALVP 48751.01, in anterior (**F**), dorsal (**G**) and ventral (**H**) views. **I**, caudal centrum, UALVP 48751.02 (anterior). **J**, caudal centrum, UALVP 50636.09 (anterior). **L-M,** maxillary fragment, UALVP 50636.04 (lingual and lateral). **N-O,** jaw fragment, UALVP 50636.05 (lingual and lateral). **P-Q**, jaw fragment, UALVP 50636.06 (lingual and ventral).

R-S, UALVP 50636.09. **T-U,** pedal ungula, UALVP 50636.07 (lateral and anterior). **V**, distal end of ulna, UALVP 50636.08. **Z**, caudal vertebra, UALVP 50637 (anterior).

Fig. 7. Miscellaneous elements from sites A and B. **A-D**, esocoid dentary, TMP 2004.23.7, in medial (**A**), lateral (**B**), dorsal (**C**), and ventral views (**D**). **E-G**, Holostean A scales: **E**, TMP 2004.93.2 (dorsal and ventral). **F**, TMP 2004.23.8 (dorsal and ventral), **G**, TMP 2004.93.5 (dorsal and ventral). **H**, Holostean B scale, TMP 2004.23.8 (dorsal and ventral). **I-J**, amiid centrum UALVP 50638.01, (anterior and dorsal). **L-M**, amiid centrum UALVP 50638.02 (anterior and dorsal). **N**, possible turtle shell fragment, UALVP 48754. **O-P**, *Cimolodon* sp. tooth TMP 2004.23.2 (occlusal and labial views). **Q-S**, *Didelphodon* sp. tooth, TMP 2004.23.1 (lingual, labial, and occlusal views).

Fig. 8. Miscellaneous ornithischian elements from sites B and C. **A**, *Pachyrhinosaurus* sp. tooth, UALVP 48752 (lingual). **B**, baby ceratopsian tooth, UALVP 50636.10 (lingual). **C**, ankylosaurid tooth, UALVP 48747 (labial). **D-G**, Pachycephalosaurid teeth: **D-E**, TMP 2004.93.1A (lingual and labial); **F-G**, TMP 2004.93.1B (lingual and labial). **H-L**, hypsilophodont tooth, TMP 2004.23.5 (lateral, labial, and lingual).

Fig. 9. Relative distribution of Kleskun Hill taxa at the three fossiliferous sites. See the text for discussion.

Fig. 10. Reconstruction of the late Campanian vertebrate fauna of the Wapiti Formation near Grande Prairie, Alberta, based on the taxa from the Kleskun Hill locality and correlative beds discussed in the text. Drawing by Lukas Panzarin.

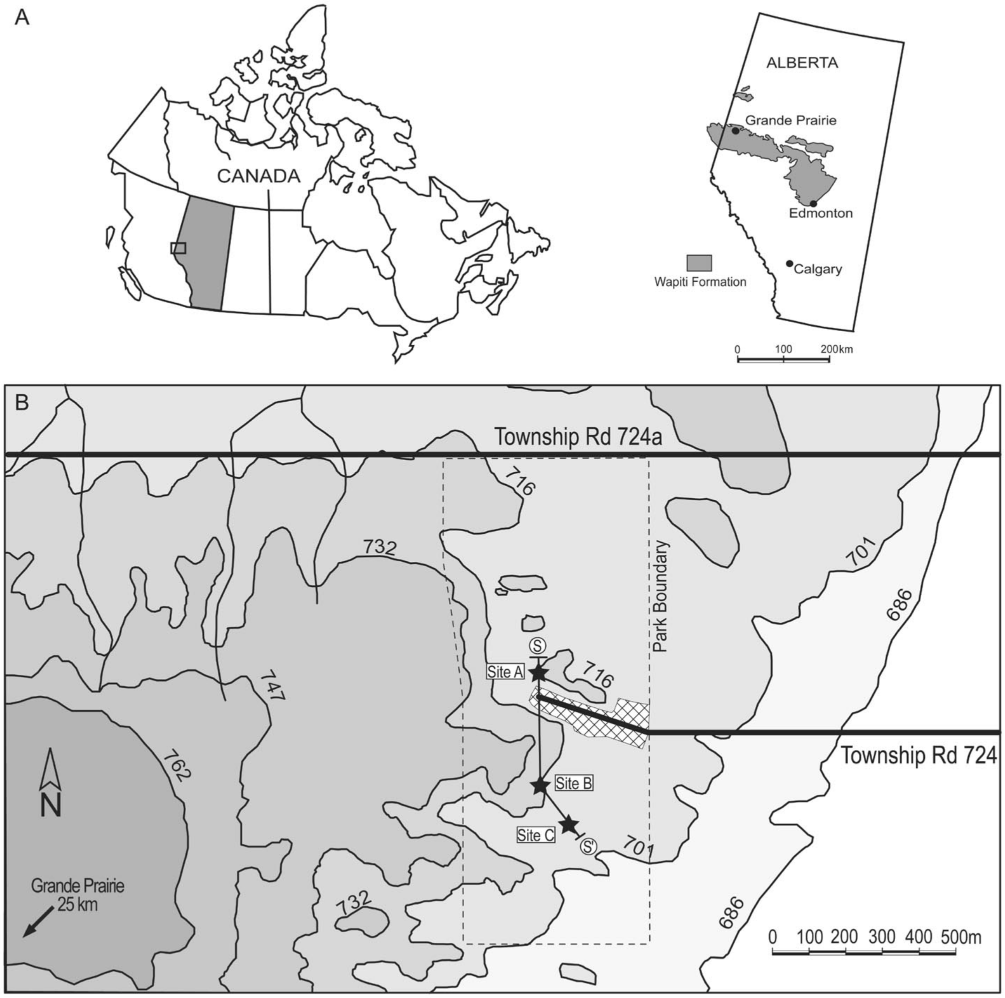
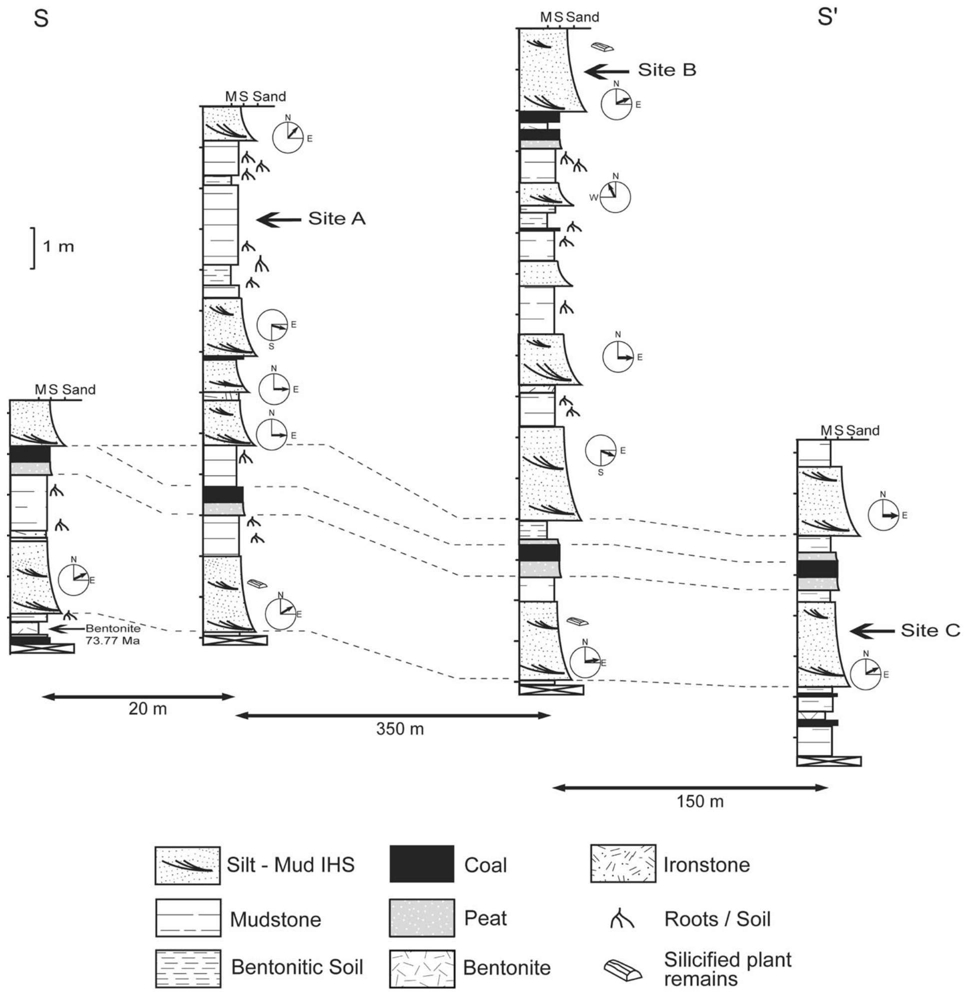

A
CANADA
ALBERTA
Grande Prairie
Edmonton
Calgary
Wapiti Formation
0 100 200km
B
Township Rd 724a
716
732
701
686
Park Boundary
Site A
716
747
762
Township Rd 724
Site B
Site C
701
N
Grande Prairie
25 km
732
686
0 100 200 300 400 500m

Figure 1



S
S'
M S Sand
Site A
Site B
Site C
1 m
Bentonite
73.77 Ma
20 m
350 m
150 m
Silt - Mud IHS
Mudstone
Bentonitic Soil
Coal
Peat
Bentonite
Ironstone
Roots / Soil
Silicified plant remains

Figure 2

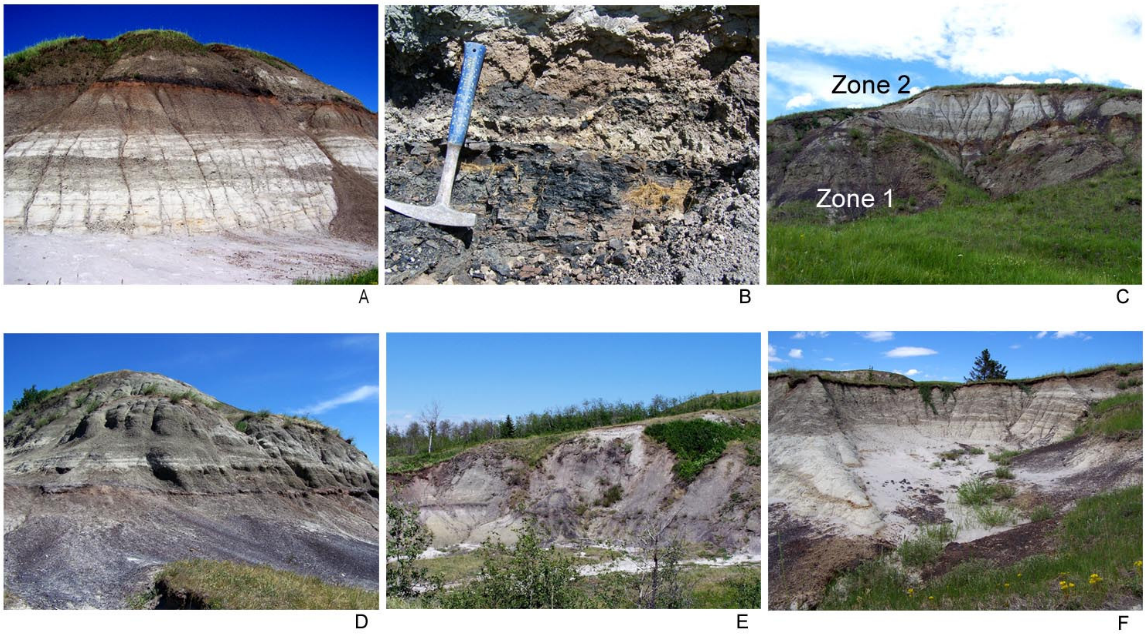


Figure 3

Taxa	Elements	N	%
Fish			
	esocoid (dentary)	1	0,4
	holostean A (scale)	3	1,2
	holostean B (scale)	1	0,4
	amiid	10	3,8
Squamates			
	lizards (skulls and isolated bones)	15	5,8
Crocodiles			
	tooth and caudal vertebra	2	0,8
Turtles			
	scute	1	0,4
Theropoda			
	Troodon (teeth)	31	11,9
	Saurornitholestes (tooth)	3	1,2
	Richardoestesia (teeth)	1	0,4
	Paronychodon (tooth)	1	0,4
	Dromaeosauridae indet. (teeth)	2	0,8
	Tyrannosauridae (teeth)	53	20,4
	small theropod claw	1	0,4
Aves			
	bird (tooth)	1	0,4
Hadrosauridae			
	teeth, skull elements and vertebras of hatchling- and nestling-size individuals	20	7,7
	teeth, vertebras of adult individuals	86	33,1
Ceratopsidae			
	isolated teeth	4	1,5
Ankylosauridae			
	isolated teeth	2	0,8
Pachycephalosauridae			
	isolated tooth	1	0,4
Ornithomimidae			
	phalanx	1	0,4
Hypsilophodontidae			
	isolated teeth	1	0,4
	caudal centrum (?)	1	0,4
Mammalia			
	multituberculate (tooth)	1	0,4
	marsupial (tooth)	1	0,4
Tendons			
	(hadrosaurs?)	16	6,2
	Total Elements	**260**	**100%**

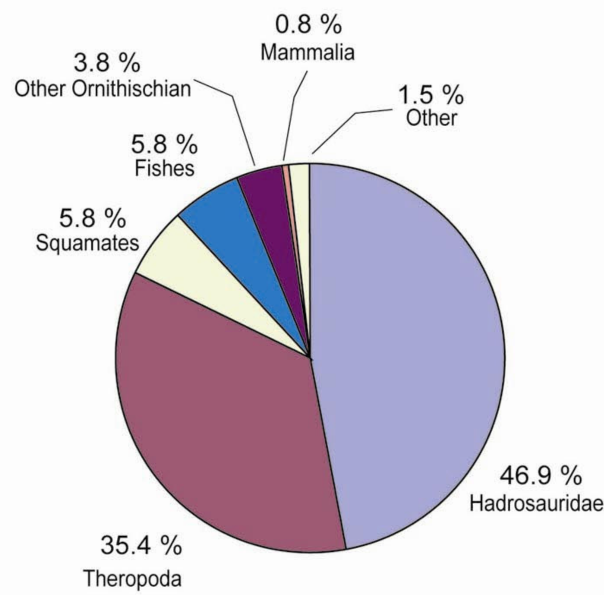


Figure 4

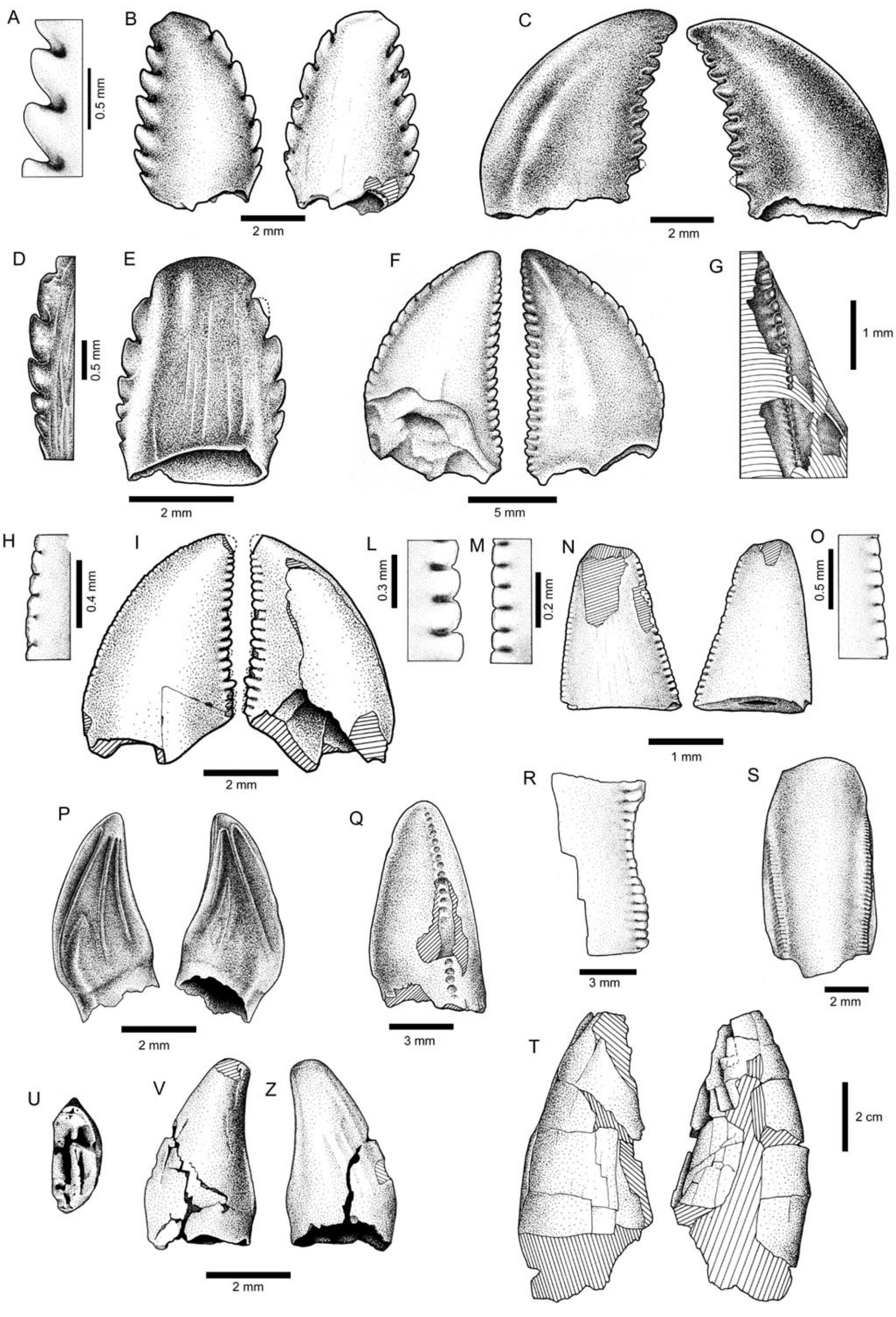

A
B
C
0.5 mm
2 mm
2 mm
D
E
F
G
0.5 mm
1 mm
2 mm
5 mm
H
I
L
M
N
O
0.4 mm
0.3 mm
0.2 mm
0.5 mm
2 mm
1 mm
P
Q
R
S
3 mm
2 mm
2 mm
3 mm
T
U
V
Z
2 cm
2 mm

Figure 5

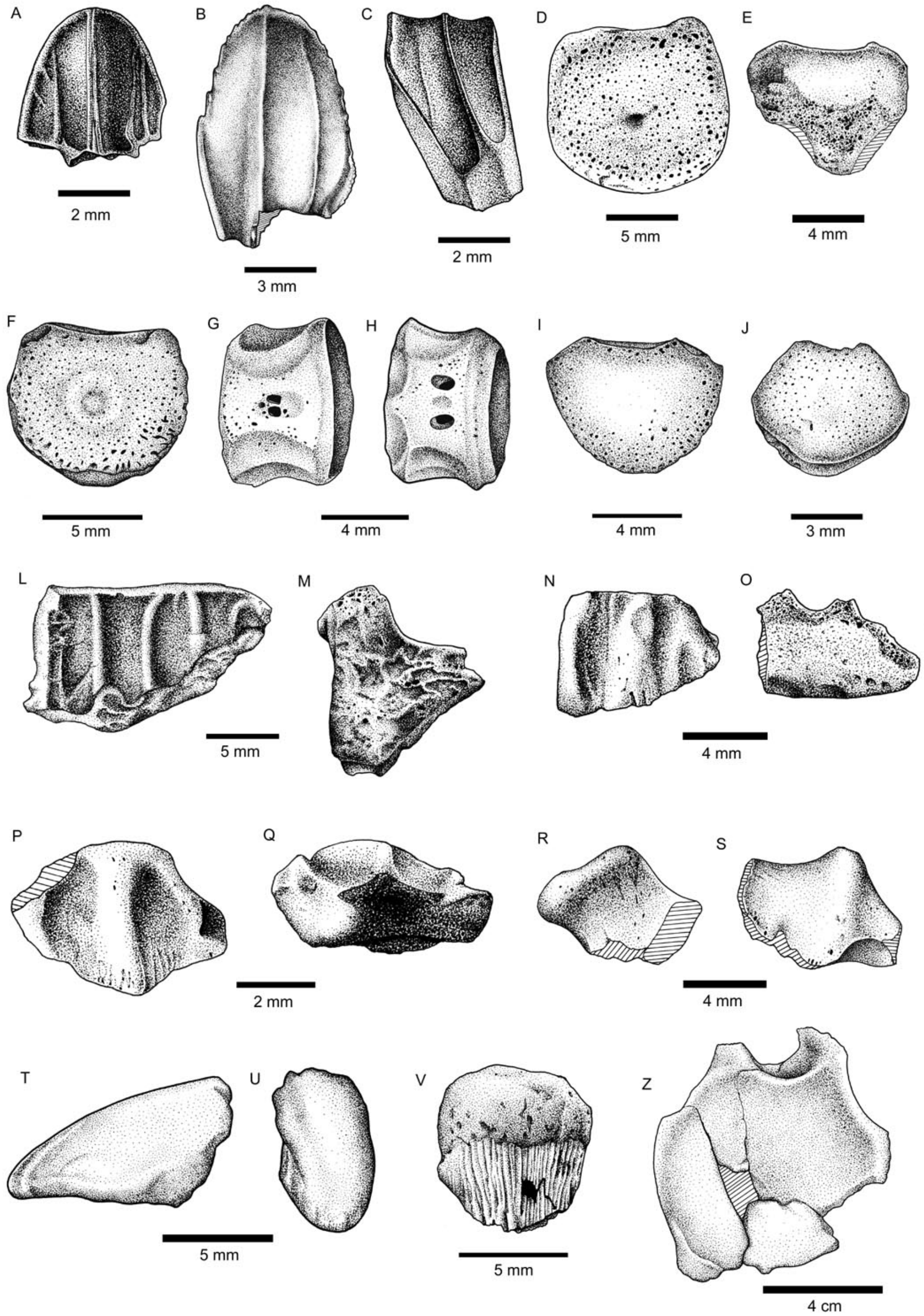

A
2 mm
B
3 mm
C
2 mm
D
5 mm
E
4 mm
F
5 mm
G
H
4 mm
I
4 mm
J
3 mm
L
5 mm
M
N
O
4 mm
P
Q
2 mm
R
S
4 mm
T
U
5 mm
V
5 mm
Z
4 cm

Figure 6

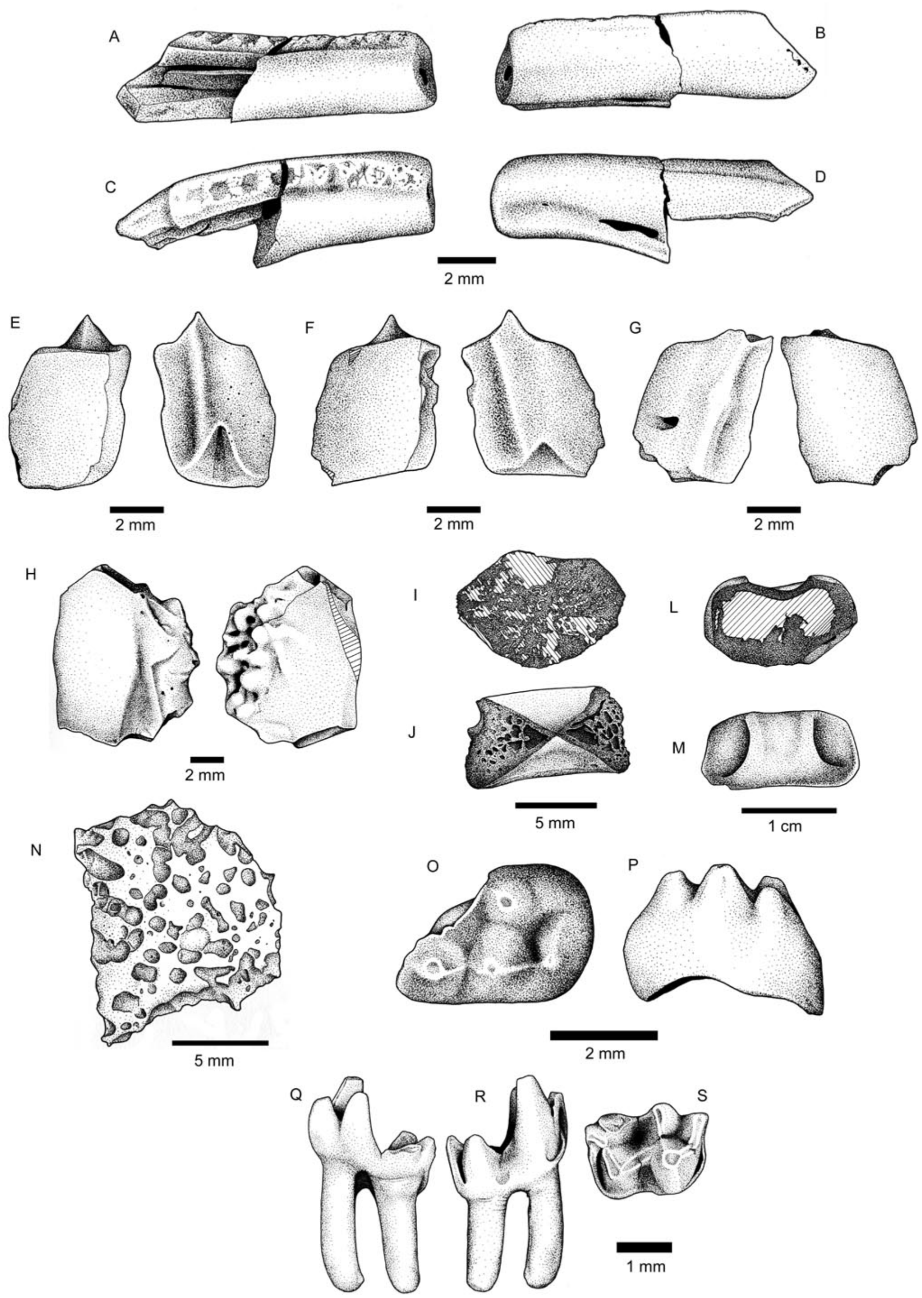


Figure 7

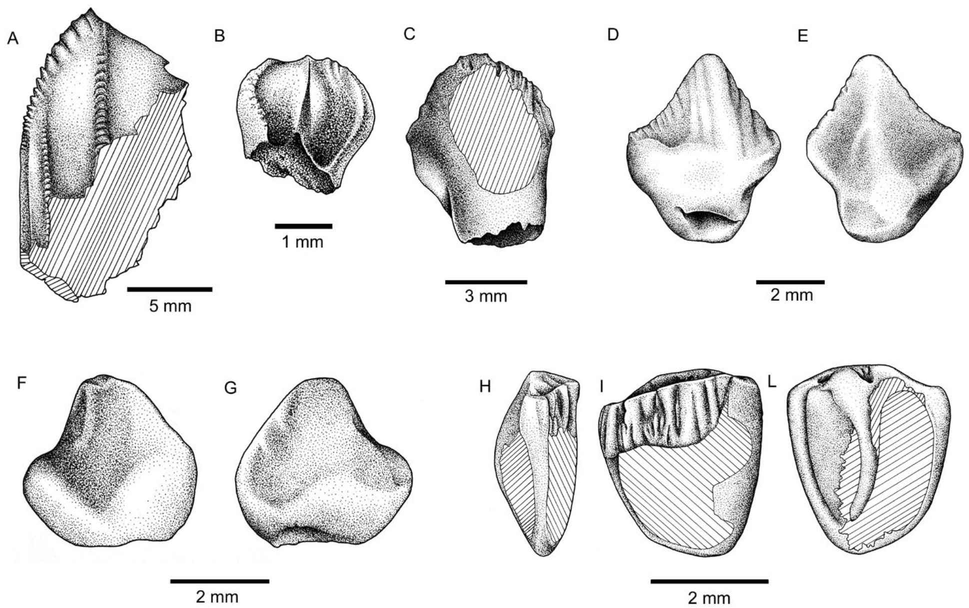


Figure 8

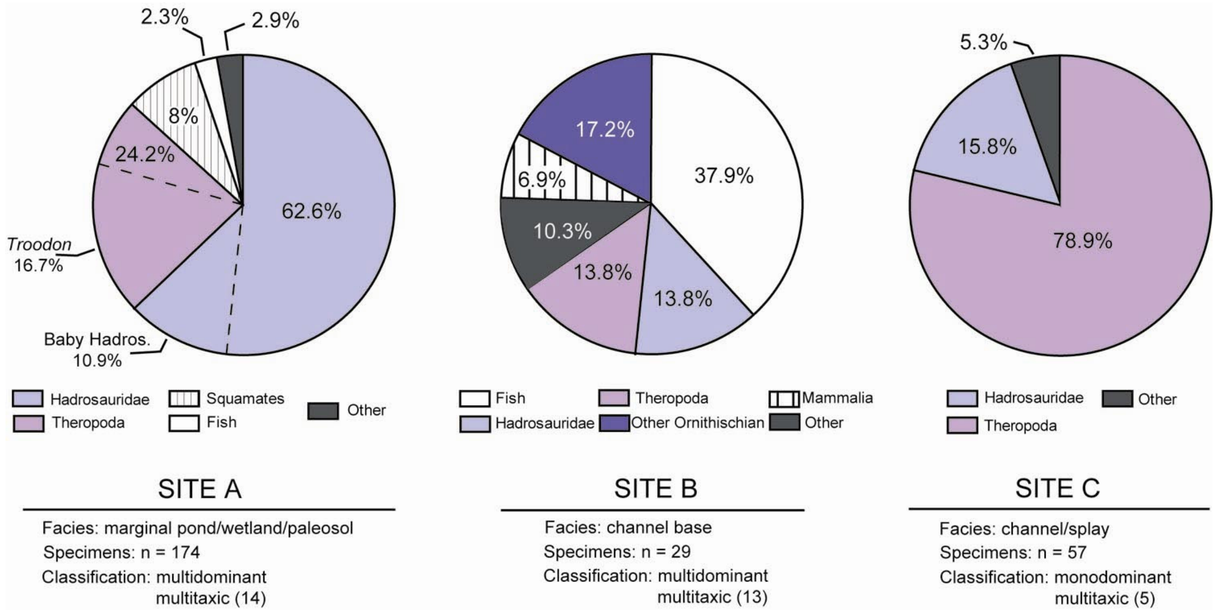

2.3%
2.9%
8%
24.2%
62.6%
Troodon
16.7%
Baby Hadros.
10.9%
Hadrosauridae
Squamates
Other
Theropoda
Fish
SITE A
Facies: marginal pond/wetland/paleosol
Specimens: n = 174
Classification: multidominant multitaxic (14)
17.2%
37.9%
6.9%
10.3%
13.8%
13.8%
Fish
Theropoda
Mammalia
Hadrosauridae
Other Ornithischian
Other
SITE B
Facies: channel base
Specimens: n = 29
Classification: multidominant multitaxic (13)
5.3%
15.8%
78.9%
Hadrosauridae
Other
Theropoda
SITE C
Facies: channel/splay
Specimens: n = 57
Classification: monodominant multitaxic (5)

Figure 9

Figure 10

Paper 5

Upper Campanian Borioteiioidean lizards from Kleskun Hill,

west-central Alberta (Wapiti Formation), Canada

Randall L. Nydam[1], Michael W. Caldwell[2], and Federico Fanti[3]

[1]Department of Anatomy, Midwestern University, Glendale, Arizona, 85308, U.S.A.;

Tel: +001 623 572 3359; Fax +001 623 572 3679; Email: rnydam@midwestern.edu

[2]Department of Biological Sciences and Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada, T6G 2E9

[3]Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Studiorum Università di Bologna, via Zamboni 67, 40126, Italy.

ABSTRACT:

New material of borioteiioidean lizards (Squamata: Scincomorpha) from northern Alberta, Canada, represent the first and northernmost record of multiple articulated skull elements from the Cretaceous of North America. Specimens were recovered from the fluvial beds of the Wapiti Formation (Campanian) within a bentonitic paleosol exposed at the Kleskun Hill Park, east of the town of Grande Prairie. Such beds accumulated during the maximum transgression of the Bearpaw Seaway (73-74 My), thus providing crucial information on lizard faunas during a time interval represented in most of coeval North American deposits by marine strata. Cranial material ascribed to *Socognathus unicuspis* give the occasion for a revision of the taxon with respect to osteologically better known *Polyglyphanodon sternbergi* from the Late Cretaceous of Utah as well as a comparison with several lizards reported from coeval strata of Mongolia. Furthermore, a new scincomorphan lizard, *Kleskunsaurus grandeprairiensis*, gen. et sp. nov., is described. Both *S. unicuspis* and *Kleskunsaurus grandprairiensis* gen. et sp. nov. are assigned to Chamopsiidae taxon nov. that also includes *Chamops*, *Leptochamops*, and several other morphologically similar taxa from the Cretaceous of North America.

Introduction

Unlike the well-preserved skulls and skeletons of Late Cretaceous lizards from Mongolia (see Gilmore, 1943a; Sulimski, 1972, 1975; Alifanov, 2000), the vast majority of Late Cretaceous lizards from North America are represented by isolated elements, particularly dentaries and maxillae (see particularly Gilmore, 1928; Estes, 1983; Gao and Fox, 1996; Nydam; 2000). The lone North American exceptions are the large-bodied *Polyglyphanodon sternbergi*, which is known from several skeletons and skulls (Gilmore 1940, 1942) and the smaller *Paraglyphanodon gazini* (Gilmore, 1943b); both taxa were recovered from the same locality in the Maastrichtian of central Utah. In some cases, attempts have been made to refer non-jaw elements (e.g., parietals, osteoderms) to these jaw-based morphotaxa (see Estes, 1983). These referrals are typically based on similarities in relative abundance in a particular locality and/or similarities in size, but remain tentative and, even in the most carefully argued cases, still represent potential chimaeras. Because most of the North American Cretaceous lizard taxa are based primarily on isolated jaw elements (e.g., jaw-based morphotaxa), they are limited when it comes to making comparisons with either better-preserved fossil taxa or members of the modern fauna. Even so, the North American fossil record of lizards from the Cretaceous is a highly diverse assemblage that includes scincomorphans, anguimorphans, and possibly some rare iguanians (Estes, 1983; Gao and Fox, 1996; Nydam, 2000; Nydam et al., 2007).

Among the scincomorphans from the Cretaceous of North America are the Borioteiioidea. This diverse group of teiid-like lizards includes *Polyglyphandon* and related taxa (e.g., *Peneteius, Dicothodon, Bicuspidon*; Nydam et al., 2007), *Chamops* and like taxa (the "chamopsiines" of Denton and O'Neil, 1995), as well as the "macrocephalosaurines" and "polyglpyhanodontines" (sensu Sulimski, 1975) from Asia (Nydam et al., 2007). In their taxonomic study of the lizards from the Cretaceous-aged sediments of western Canada, Gao and Fox (1996) described numerous taxa of "teiids" (= borioteiioids) effectively expanding the number of taxa in North America from four to eleven genera, all diagnosed on the basis of isolated jaw material. Among these taxa is *Socognathus unicuspis,* which is described from isolated dentaries and maxillae from the Oldman Formation (Campanian) of southeastern Alberta, Canada.

Herein we describe several specimens of articulated cranial material of *Socognathus unicuspis* and a new taxon of lizard from the late Campanian Wapiti Formation of west-central Alberta. These specimens are unique in that they represent the northernmost occurrence of fossil lizards in North America, but more importantly they are the first record of articulated skull elements of small-bodied lizards from the Cretaceous of North America.

Anatomical abbreviations—C, centrum; **D**, dentary; **F**, frontal; **HA**, haemal arch; **IMS**, intramandibular septum; **J**, jugal; **La.Fac.**, lacrimal articulation facet; **Mn**, mandible (individual elements indiscernible); **Mx**, maxilla; **Mx.Fac.**, maxillary articulation facet; **Na.Fa.**, nasal articulation facet; **P**, parietal; **PD**, postdentary (individual elements indiscernible); **Pl**, palatine; **Pmx**, premaxilla; **PrF**, prefrontal; **PsF**, postfrontal; **ScO**, scleral ossicles; **Tb**, tooth base.

Institutional Abbreviations—TMP, Royal Tyrrell Museum of Paleontology, Drumheller, Alberta, Canada. **UALVP**, University of Alberta Laboratory for Vertebrate Paleontology, Edmonton, Canada.

Locality, sedimentology and stratigraphy

Specimens described in this study were found within a greenish, bentonitic paleosol at the Kleskun Hill Park, approximately 25 km east of Grande Prairie, west-central Alberta (Fig. 1). Fluvial deposits exposed in the area belong to the Late Cretaceous (Campanian-Maastrichtian) Wapiti Formation, and consist primarily of interbedded, organic-rich siltstone and mudstone, extensive coal seams and light-grey bentonitic sandstones (Allan and Carr, 1946; Dawson et al., 1994; Fanti, 2007, Fanti and Miyashita, in press). Yellow to greenish altered volcanic ash beds are fairly common within this stratigraphic interval, and represent a reliable tool for dating exposures at the fossil site: a bentonite bed at approximately 10 meters below the layer where specimens were recovered yielded an $^{40}Ar/^{39}Ar$ of 73.77 ± 1.46 My (D. Eberth, pers. comm., in Fanti, 2007; Fig. 2). Consequently, Kleskun Hill fluvial deposits are nearly equivalent in age to the maximum transgression of the Bearpaw Seaway (*Baculites compressus* zone, 73.4 Ma, Obradovich, 1993), a reference marine unit in central and southern Alberta.

Paleoenvironmental interpretation

Detailed sedimentological analyses at the Kleskun Hill Park indicate a paleoenvironment characterized by high-sinuosity, low energy, meandering fluvial system associated with widespread ponds and oxbow lakes where fine, organic-rich deposits accumulated undisturbed. Well-developed peat and coal beds also indicate luxuriant vegetation well-adapted to a semi-permanent high water table as well as well developed, acidic soils (Fig. 2). Silicified roots, tuffaceous concretions, and shattered plant and vertebrate remains are ubiquitous within the fossiliferous layer. It ranges in thickness between 60 and 75 cm and is light green to olive in colour. The predominantly bentonitic composition and the high mobilization of silica is probably a reflection of intense lisciviation processes of a well developed volcanic ash soil (and associated devitrification) under high water table conditions in a humid, tropical environment. During this process, organic remains such as roots, plant remains and bone fragments, acted as nuclei for the development of extremely fine, quartz-rich nodules and concretions. As a result, specimens preserved within this layer are not only in pristine conditions but also in their original three-dimensional shape.

In addition, examination of the muddy channel fill deposits in the area also led to the discovery of a complex microfossil assemblage that to date include dinosaurs, birds, fresh water fishes and amphibians, and mammals, all previously reported from equivalent non-marine deposits of the Belly River and Edmonton groups of Alberta. (Tanke, 2004; Fanti and Miyashita, in press). Interestingly, the site is exclusively dominated by relatively small sized terrestrial taxa (i.e. amphibians, squamates, small theropod dinosaurs, and mammals) that to date haven't been recovered elsewhere in the area, supporting a geographically restricted ecological niche as well as a strong connection between environment and specialized paleofauna.

Materials and methods

For the osteological description, light micrographs of the principal specimens were taken using a Nikon COOLPIX 4500 digital camera mounted to a dissection microscope. Scanning electron micrographs (SEM) were taken on a JEOL 6301 scanning electron microscope (1 kV, 44 mm working distance). Line images were created using Adobe Illustrator CS3 to trace micrographs.

Osteological terminology follows that of Oelrich (1956) except where noted.

SYSTEMATIC PALAEONTOLOGY

REPTILIA Linnaeus, 1758

SQUAMATA Oppel, 1811

SCINCOMORPHA Camp, 1923

cf. Borioteiioidea Nydam et al., 2007

Chamopsiidae new taxon

Etymology—Named for *Chamops segnis* Marsh, 1892, the earliest described member of the clade.

Type species—*Chamops segnis*.

Referred taxa—*Gerontoseps irvinensis* Gao and Fox, 1991; *Glyptogenys ornata* Gao and Fox, 1991; *Harmondontosaurus emeryensis* Nydam, 2002; *Haptosphenus placodon* Estes, 1964; *Leptochamops dentinticulatus* Gilmore, 1928; *L. trinax* Gao and Fox, 1991; *Meniscognathus altmani* Estes, 1964; *Meniscognathus molybrochoros* Nydam and Voci, 2007; *Socognathus unicuspis* Gao and Fox, 1991; *Stypodontosaurus melletes* Gao and Fox, 1996; *Trippenaculus eatoni*, Nydam and Voci, 2007.

Diagnosis—Borioteiioidean lizards that differ from the Asian (*Macrocephalosaurus gilmorei, M. chulsanensis, Cherminsaurus kozlowskii, Darchansaurus estesi*) and other North American (*Bicuspidon numerosus, B. hatzegiensis, Dicothodon moorei, D. cifelli, D. bajaensis, Polyglyphanodon sternbergi*) borioteiioids in having a long, massive mandibular symphysis extending posteriorly 4–5 tooth positions and forms the superior and inferior margins of the anteriormost portion of the Meckelian groove. Further differs from the aforementioned taxa and *Macrocephalosaurus gilmorei, M. chulsanensis, Cherminsaurus kozlowskii, Darchansaurus estesi,* and *Erdenetesaurus robinsonae* in teeth tending to be massive with a mid-shaft swelling ("barrel-shaped"), tooth crowns tending to have mesial and distal accessory ridges often forming cusps, teeth widely spread along the tooth row. Further differs from *B. numerosus, B. hatzegiensis, D. moorei, D. cifelli, D. bajaensis,* and *Po. sternbergi* in tooth crowns lacking transverse orientation or mediolateral expansion. Differs from *Prototeius stageri* in lacking an intramandibular septum below the posterior half of the dentary tooth row and in having teeth in the anteriormost portion of the dentary tooth row that are not procumbent to only very weakly procumbent.

Remarks—This new taxon is erected as a replacement for Chamopsiinae Denton and O'Neil, 1995. Denton and O'Neil (1995) erected Chamopsiinae as a subfamily of Teiidae (see Nydam et al., 2007) that included *Chamops segnis*, *Leptochamops denticulatus*, *Meniscognathus altmani* Estes, 1964, all from the Western Interior of North America, and *Prototeius stageri* Denton and O'Neil, 1995 from New Jersey. Because the taxa from the Western Interior are only known from isolated jaws (except possibly *C. segnis*, but see below), four of the six diagnostic characters for Chamopsiinae (temporal bones not reduced, retroarticular process lacking well developed medial flange, parietal foramen present, parietal longer than wide) can only be confirmed for *Pr. stageri*. Estes (1964) tentatively referred a frontal and a parietal from the Lance Formation to *C. segnis*. However, since there are several lizard taxa known from the Lance Formation and such a referral, though not necessarily incorrect, means that that the characters of this parietal (presence of parietal foramen, parietal longer than wide) are equally tentative for *Chamops*. Also, the complete mandible of *Chamops* sketched by Estes (1983) is not based on known postdentary materials and cannot be used to determine the actual condition of the retroarticular process. The character concerning the separation of the surangular and the coronoid by the IMS is additionally problematic as all of the specimens of chamopsiid taxa from the Western Interior that we have studied possess an IMS than does not extend posteriorly past the midpoint of the tooth row. Many of these taxa (*C. segnis, L. denticulatus, L. thrinax, So. unicuspis, Sp. simplex, Gl. ornata, Ge. irvinensis, M. altmani*, and *St. melletes*) have a groove on the ventral surface of the subdental shelf for the tongue-in-groove articulation with the splenial. In *C. segnis* and *Ge. irvingensis* the posterolateral portion of this groove deepens to accommodate the anteromedial process of the coronoid. The result of this deepening is a distinct, ventrally directed bony flange. This flange likely separated the surangular from the anteromedial process of the coronoid, but not the Meckel's cartilage from the mandibular neurovascular bundle. *Prototeius* has been described to possess an IMS (Denton and O'Neil, 1995), but it is not clear if this feature is equivalent to the flange forming the lateral border of the splenial articulation. *Prototeius* also lacks the hypertrophied symphyseal region of the mandible and does possess procumbent anterior teeth of the dentary. As such we do not included *Prototeius* in the Chamopsiidae at this time. It is unclear what relationship exists between *Prototeius* and the North American Borioteiioidea.

Socognathus unicuspis Gao and Fox, 1996

(Figs. 3-5)

Holotype—UALVP 29739, incomplete left dentary.

Referred specimens—UALVP 29910-26611, incomplete tooth-bearing maxillae; UALVP 29732, 29736, 29740, 29743-29745, and TMP 82.24.57, incomplete tooth bearing dentaries.

Type Locality and Horizon—Railway Grade locality, Oldman Formation, Campanian; southeastern Alberta (see Gao and Fox, 1996).

New Material, Locality, and Horizon—UALVP 50958 (KH.2007.039), rostral portion of skull preserving the anterior portions of the right and left maxillae and the right and left dentaries, and a partial ?palatine; UALVP 50963, partial skeleton preserving fragmentary cranial elements and the centra of two caudal vertebrae; UALVP 50961, anterior portion of a right maxilla. Wapiti Formation, Kleskun Hill Park locality, approximately 25 km northeast of Grande Prairie, Alberta, Canada.

Revised Diagnosis— Late Cretaceous borioteiioid differing from other chamopsiids in marginal teeth not crowded along tooth row, but variable in spacing and orientation; teeth tall, with straight mesial and distal sides, somewhat compressed mesiodistally and recurved; tooth crowns mediolaterally concavo-convex, unicuspid with cusp pointed, inclined somewhat posterolingually. Differs further from *Gerontoseps irvingensis* in having moderately strong mesial carina and weaker distal carina (i.e., non-symmetrical) curving lingually from apical cusp; tooth attachment subpleurodont, with lateral parapet low, about one-third tooth height. Differs further from *Stypodontosaurus melletes* in having tooth crowns more acutely pointed, not spatulate. Differs further from *Sphenosiagon simplex* in teeth set at an oblique angle to the long axis of the jaw. Differs further from *Chamops* and *Leptochamops* in interior alveolar foramen of maxilla opens more anteriorly; articulation surface for palatine significantly deeper and anteriorly more extensive.

Remarks—The diagnosis of *Socognathus unicuspis* provided by Gao and Fox (1996) included the form of the massive mandibular symphysis, which is recognized herein to be a feature diagnostic of the more inclusive Chamopsiidae. Additionally, Gao and Fox (1996:28) noted that the features of the maxilla "supplement those of the dentition in distinguishing *Socognathus* from *Chamops* and *Leptochamops*." We agree with their assessment and have included these features in the diagnosis. We have additionally added to the diagnosis the specific differences distinguishing Socognathus from other chamopsiids with unicuspid teeth (e.g., *Gerontoseps*, *Sphenosiagon*, and *Stypodontosaurus*).

DESCRIPTION OF NEW MATERIAL

Skull Elements–UALVP 50958 (Figs. 3, 4) is the incomplete rostral portion of a skull. It preserves partial right and left maxillae, partial right and left dentaries, and a partial left ?palatine. The left maxilla is broken into two pieces and is missing most of the dorsal process, the premaxillary process, and the posterior, or jugal, process. The tooth-bearing portion of the maxilla has 10 complete, or nearly complete, teeth; four on the anterior fragment and six on the posterior fragment. The supradental is only exposed on the posterior fragment. In dorsal view the supradental shelf is mediolaterally broad and has two distinct fossae. The anteriormost of the fossae is anteroposteriorly elongate and bounded posteriorly by a semicircular bony ridge. The more posterior fossa is a narrow depression just medial to the remnant of the dorsal process. This depression is most likely the anterior portion of the groove for the articulation of the jugal. Medial and parallel to supradental shelf is a bone, or possibly two bones, that are possibly the remnants of the palate (most likely palatine based on position relative to the maxilla).

Opposite of the left maxilla and anterior and inferior to the ?palatal bones is the partially preserved right maxilla. The right maxilla only preserves the tooth-bearing portion of the element and is missing the premaxillary, posterior, and much of the dorsal processes. There are 10 tooth spaces preserved that contain five complete and five partial teeth. The remnant of the dorsal process just superior to the tooth row is pierced by 3-4 labial foramina, the middle two of which are conjoined and form a “figure-8” outline.

The left dentary lies just inferior to the left maxilla and slightly posterior to what would have been its original position relative to the maxilla. Only the symphysial and the anterior portion of the lateral parapet of the left dentary are preserved and the teeth of the left maxilla overlap and obscure much of the lateral parapet. The symphysial surface of the left dentary is separated into ventral and dorsal surfaces by the continuation of the Meckelian groove. The ventral surface is narrow and smooth and the dorsal surface obscured by matrix, but it is possible to tell that it is continuous with the subdental shelf. The subdental shelf is partially exposed posterior to the symphysis. It is tall (approximately 1/2 tooth height) anteriorly and quickly tapers posteriorly in conjunction with the presence of the articulation facet for the splenial. The lateral surface of the anterior portion of the left dentary is pierced by a series of small, closely spaced mental foramina. Based on the position the articulation facet on the dentary, the splenial extended anteriorly to the mandibular symphysis. The right dentary is inferior and medial to the right maxilla. However, the right dentary is heavily damaged and no useful morphological details are preserved.

The maxillary teeth are large and have strongly convex labial surfaces such that the apex of each tooth is directed inferomedially. In lateral view the crowns are weakly trifid with a tall central apex and lower mesial and distal expansions of the carinae. In apical view the outline of the crown traces a weak W-shape. The lingual surfaces of the teeth are mostly obscured by matrix, but two of the teeth on the right maxilla have been exposed sufficiently to see the lingual surfaces in apical view. The central portion of the lingual surface of the crown that is continuous with the apex is medially expanded to form a central ridge. On either side of this ridge are shallow fossae associated with the mesial and distal expansions of the crown. The tooth bases labiolingually wide and mesiodistally compressed. The bases of the teeth are not sufficiently exposed to determine if resorption pits are present.

UALVP 50960 is a skull fragment preserving a nearly complete premaxilla, fragments of the left maxilla and dentary, as well as the centra of two vertebrae. The nasal process of the premaxilla is broken near its base, but it was apparently narrow and triangular in cross-section. The lateral processes of the premaxilla are short and robust. The external surface of the element is smooth. There are three teeth preserved on the maxilla and spaces for an additional four teeth. The median tooth is complete and it is tall, columnar, sharply pointed, and the labial surface of the crown is curved lingually near the tip. On the left side the distal end of the medial flange of the premaxillary process of the maxilla is still in articulation with the posterior surface of the left lateral process of the premaxilla, but we are unable to determine if reaches the incisive process. The internal surface of the premaxilla is not exposed.

Of the left maxilla only the aforementioned portion of the premaxillary process and three teeth are still present. The teeth are poorly preserved, but are morphologically similar to those of UALVP 50958. The medial surface of the anteriormost portion of the left dentary is visible. The subdental shelf is prominent, but not tall. The subdental gutter is narrow and shallow. There are seven partial teeth preserved on the dentary. The anteriormost of these teeth is broken, but was clearly procumbent. The exposed lingual surfaces of the two best-preserved teeth are straight, smooth, and columnar. The crowns of all of the teeth are missing.

UALVP 50961 is the anterior portion of a right maxilla. The lateral surface is smooth and pierced by two labial foramina that open anterolaterally. The premaxillary process is mediolaterally broad and had forked. The medial and anterior projections of the premaxillary process are broken at their bases. The dorsal process rises steeply and at its base is the small opening of the anterior superior alveolar foramen. There is a single tooth preserved inferior to the anterior margin of the dorsal process. The tooth is massive, laterally convex, and rotated posteriorly about 45 degrees. The lateral parapet forms a prominent, inferiorly directed flange adjacent to the tooth.

Postcranial Elements–There are several fragmentary remains of post cranial elements co-preserved in many of the blocks that also contains cranial elements. The most noteworthy of these postcranial elements are on specimen UALVP 50963 and include two articulated caudal vertebrae and an associated haemal arch that preserved on a block with what appears to be a fragment of a dentary preserving the anterior portion of the tooth row and possibly an articulated splenial. Both of the vertebrae are exposed in lateral view (Fig. 6A, B) and each has a long centrum and a cross-sectional view (Fib. 6C) shows a low neural arch. No neural or transverse processes are discernable. The haemal arch (Fig. 6A, C) is poorly preserved and otherwise unremarkable. These specimens represent the first postcranial elements that can be confidently referred to a known taxon of chamopsiid lizard.

SCINCOMORPHA Camp, 1923

Cf. Chamopsiidae

Taxon indet.

Kleskunsaurus genus nov.

(Figs. 7-8)

Etymology—For Kleskun Hill Park, where the type and only known species was found.

Type species— *Kleskunsaurus grandeprairiensis* sp. nov, see below.

Type Locality and Horizon—Kleskun Hill locality (see above).

Diagnosis—As for type and only known species.

Kleskunsaurus grandeprairiensis sp. nov.

Etymology—For the town of Grande Prairie, Alberta located near the type locality.

Holotype—UALVP 50959.

Diagnosis—Differs from *Chamops*, *Gerontoseps*, *Glyptogenys*, *Haptosphenus*, *Leptochamops*, *Sphenosiagon*, *Stypodontosaurus* in having teeth much less robust. Differs from *Mensicognathus* in teeth more widely spaced and not mediolaterally compressed. Differs from *Gilmoreteiius*, *Cherminsaurus*, *Darchansaurus* in having posterior articulation of nasals onto frontal separated by a median frontal ridge such that the nasals form two distinct tabs that overlap the frontal (shared with *Polyglyphanodon sternbergi*). Differs further from *P. sternbergi* in having frontal with posterolateral expansion (not restricted by enlarged postfrontal).

Remarks—referral to Chamopsiidae is likely, but treated as tentative pending the recovery of a more complete mandibular ramus.

DESCRIPTION

Skull Elements–UALVP 50659 is a incomplete skull of a small lizard preserving the partial remains of the bones bordering the left orbit, portions of the right and left maxillae, and right and left dentaries.

Frontal: the frontal has a nearly complete nasal process, but only the left margin of the rest of the element is preserved. The nasal process is narrow, long, and pointed anteriorly. A median septum separates the articular facets for the right and left nasals. The dorsal surface of the remaining portion of the frontal is too eroded to determine if it was smooth or ornamented. The anterior half of the medial border of the orbit is formed by the frontal process of the prefrontal as it articulates with the frontal. The lateral margin of the frontal forms the posterior half of the medial border of the orbit and turns laterally to form part of the posterior border of the orbit. The posterior margin of the frontal is poorly preserved and the articulations with the parietal and postfrontal are not discernible.

Prefrontal: the prefrontal is large, poorly preserved, triangular (as exposed), and forms most of the anterior border of the orbit. The central portion of the prefrontal is massive and is missing much of its cortical bone covering. The prefrontal contacts the posterior margin of the dorsal process of the maxilla, but the prefrontal is nearly horizontal when in life it was almost certainly more vertical in orientation. The lacrimal is missing and the prefrontal is not sufficiently exposed to determine the shape and position of the lacrimal foramen.

Jugal: the jugal has a well-preserved maxillary process, but the temporal process is poorly preserved and incomplete. The maxillary process is expanded dorsally and the lateral surface has articulation facets for the maxilla and presumably the lacrimal. The maxillary facet is long, triangular, tapers posteriorly, and involves most of the maxillary process. The lacrimal facet is small, triangular and just superior the maxillary facet at the anterior end of the maxillary process. The temporal process extends posterodorsally towards the presumed position of the frontal-postfrontal articulation. The element is too poorly preserved to provide any addition morphological details (e.g., presence/morphology of quadratojugal process).

Maxilla: only the posterior portion of the maxilla is preserved on either side and the right is the better of the two. The posterior process of the maxilla is long and narrow, extending posteriorly to nearly the midpoint of the orbit. The dorsal process is broken, but was evidently tall. Four labial foramina are present just superior to the lateral parapet. The preserved portion of the maxilla bears approximately nine closely spaced, columnar, teeth with subpleurodont attachment. No tooth crowns are preserved.

Dentary: the lateral surface of the left dentary is exposed in the block, but it is missing the anteriormost and posteriormost ends. The preserved portion is straight and strongly laterally convex. The broken shafts of some of the dentary teeth are visible in cross-section. The teeth are closely spaced and have narrow shafts. As with the maxilla, there are no preserved tooth crowns.

DISCUSSION AND CONCLUSIONS

Lizard-bearing horizons have been reported from various late Cretaceous-aged alluvial deposits in western North America: such layers share an almost identical lithological and paleoecological signature, representing primarily overbank or crevasse splays originated within a meandering fluvial setting (Sternberg, 1951; Prothero and Estes, 1980; Gao and Fox, 1991, 1996; Denton and O'Neill, 1995; Nydam, 2002; Nydam and Cifelli, 2002a, b; Nydam et al., 2007). As a consequence of these relatively high-energy depositional environments, responsible also for pre-burial transportation and deterioration of skeletal remains, such localities almost exclusively preserve fragmentary and disarticulated microvertebrate fossils. Furthermore, sedimentological analyses also support humid climatic conditions and environments characterized by high-water table conditions and permanent waterlogged areas (such as ponds, marshes, and small lakes). Similar conditions characterize the Early Cretaceous deposits of the Tetori Group of Japan where six distinct lizard taxa have been recovered from a vegetated subaerial swamp environment subject to short periods of flooding (Evans and Manabe, 2008). These conditions are remarkably different from those observed in age-equivalent deposits of Mongolia (i.e. Djadokhta, Barun Goyot, and Nemegt formations: Gao and Fox, 1991; Sulimsky, 1975; Norell and Gao, 1997; Alifanov, 2000, and references therein) characterized by diverse fluvial and sand-storm originated deposits as well as dryer climatic conditions. Recently, lizard eggs from India were also recovered from densely vegetated areas marginal to a carbonaceous, tidally influenced lagoon (Shukla and Srivastava, 2008). Similar environmental conditions have been reconstructed in the Lower Cretaceous locality of Pietraroia (Italy), where an extremely fine-grained limestone preserved articulated specimens as well as soft tissues (Evans et al., 2004, 2006). The bentonitic paleosol at the Kleskun Hill locality in which lizard articulated specimens were recovered may represent a new source for vertebrate microfossils elsewhere. These peculiar lithologies are 1) easily identifiable and traceable in the field, 2) amongst the finest-grained terrestrial sediments, 3) originated through relatively rapid ashfall and not by fluvial transportation (thus avoiding pre-burial transportation or disarticulation), and 4) datable using consolidate radioisotopic techniques (either TIMS or Ar/Ar methodologies).

Lizard remains in western North America are typically found in vertebrate microfossil sites characterized by high-diversity, multidominant assemblages (*sensu* Eberth et al., 2007), where they are commonly outnumbered either in absolute diversity or recovered specimens. Significantly, in the case of the Kleskun Hill locality, lizards remains represent 8% of all recovered specimens and 21% of identified taxa (Fanti and Miyashita, in press). Such values, coupled with environmental evidences of a suitable habitat (i.e. abundant vegetation, soft paleosols and permanent fresh water), confirm the uniqueness of this locality.

The two skulls recovered from the Kleskun Hill Park are significant additions to a growing record of the newly recognized Chamopsiidae. Additionally, these skulls also represent the second recorded example (*Polyglyphanodon sternbergi* and *Paraglyphanodon utahensis* are the first) of articulated cranial material that includes both upper and lower dental arcades of lizards from the Late Cretaceous of North America. As such, they represent a unique insight into the small vertebrate, and in particular, small squamate diversity during the Late Cretaceous of North America. These specimens are all the more important as they represent the northernmost record of any lizards from North America's Late Cretaceous. The *Socognathus unicuspis* specimens provides the opportunity for revision of this taxon and more meaningful comparison to osteologically well-understood *Polyglyphanodon sternbergi* from the Late Cretaceous of Utah, as well as *Gilmoreteius* (=*Macrocephalosaurus*;Langer 1998), *Darchansaurus, Erdenetesaurus,* and *Cherminsaurus* from the Late Cretaceous of Mongolia.

ACKNOWLEDGEMENTS

For assistance with preparation, we thank L. A. Lindoe, University of Alberta Laboratory for Vertebrate Palaeontology, Edmonton. We also thank G. Braybrook, University of Alberta Department of Earth and Atmospheric Sciences, for assistance with the SEM, T. Miyashita and S. Graber, who found the first elements at the Kleskun Hill localtiy; R. Hunt, K. Ormay, N. Ormay, D, Mittra, P. Currie and E. Koppelhus for their support in the field. FF thanks the Grande Prairie Regional College for logistic support. Funding to FF was provided by the Jurassic Foundation, the Dinosaur Research Institute, the Fondazione Cassa di Risparmio in Bologna, and the Museum of Geology and Paleontology Giovanni Capellini (University of Bologna), professors Gian Battista Vai (University of Bologna) and Octavian Catuneanu (University of Alberta) (supervisors of FF). Additional funding was provided in part by a Midwestern University Research Grant to RN, and an NSERC Discovery Grant (#238458-01) to MC.

LITERATURE CITED

Alifanov, V. 2000. The fossil record of Cretaceous lizards from Mongolia, p. 368-389 in M. Benton, M., Shishkin, D.,Unwin, and E. Kurochkin (eds.), The age of dinosaurs in Russia and Mongolia. Cambridge University Press, Cambridge.

Allan, J., and J. Carr. 1946. Geology and Coal Occurrences of Wapiti-Cutbank Area, Alberta. Research Council of Alberta Report 48:50 pp.

Camp, C. 1923. Classification of the lizards. Bulletin of the American Museum of Natural History 48:289-481.

Dawson, F., C. Evans, R. Marsh, and R. Richardson. 1994. Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin; 18 pp. in G. Mossop and I. Shetson (eds.), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary.

Denton, R., and R., O'Neill. 1995. *Prototeius stageri*, gen. et sp. Nov., a new teiid lizard from the Upper Cretaceous Marshalltown Formation of New Jersey, with a preliminary phylogenetic revision of the Teiidae. Journal of Vertebrate Paleontology 15:235-253.

Eberth, D., M. Shannon., and B. Noland. 2007. A bonebeds database: classification, biases, and patterns of occurrence; pp. 103-219 in R. Rogers, D. Eberth, and A. Fiorillo (eds.), Bonebeds: genesis, analysis, and paleobiological significance. The University of Chicago Press, Chicago and London.

Estes, R. 1964. Fossil vertebrates from the Late Cretaceous Lance Formation, eastern Wyoming. University of California Publications in Geological Sciences 49:1-169.

Estes, R. 1983. Sauria Terrestria, Amphisbaenia. Gustav Fisher Verlag, Stuttgard and New York, 249 pp.

Evans, S., and M., Manabe. 2008. An early herbivorous lizard from the Lower Cretaceous of Japan. Palaeontology 51:487-498.

Evans, S., P. Raia, and C. Barbera. 2004. New lizards and rhynchocephalians from the Lower Cretaceous of southern Italy. Acta Palaeontologica Polonica 49:393-408.

Evans, S., P. Raia, and C. Barbera. 2006. The Lower Cretaceous lizard genus *Chometokadmon* from Italy. Cretaceous Research 27:673-683.

Fanti, F. 2007. Unfolding the geological history of the North: new comprehensive survey of the Wapiti Formation, Alberta, Canada; pp. 33-38 in D. Braman (ed.), Ceratopsian Symposium, Short Papers, Abstracts and Programs. Royal Tyrrell Museum, Drumheller.

Fanti, F., and T., Miyashita. In press. A high latitude vertebrate fossil assemblage from the Late Cretaceous of west-central Alberta, Canada: evidencee for dinosaur nesting and vertebrate latitudinal gradient. Palaeogeography, Palaeoclimatology, Palaeoecology.

Gao, K., and R., Fox. 1991. New teiids lizards from the Upper Cretaceous Oldman Formation (Judithian) of southwestern Alberta, Canada, with a review of the Cretaceous record of teiids. Annals of the Carnegie Museum 60:145-162.

Gao, K., and R., Fox. 1996. Taxonomy and evolution of Late Cretaceous lizards (Reptilia:Squamata) from western Canada. Bulletin of the Carnegie Museum of Natural History 33:1-107.

Gilmore, J. 1928. Fossil lizards of North America. National Academy of Sciences Memoir 22:1-201.

Gilmore, J. 1940. New fossil lizards from the Upper Cretaceous of Utah. Smithsonian Miscellaneous Collections 99:1-3.

Gilmore, J. 1942. Osteology of *Polygliphanodo*n, an Upper Cretaceous Lizard from Utah. Proceeding of the United Stated National Museum 92:229-265.

Gilmore, C. 1943. Fossil lizards of Mongolia. Bulletin of the American Museum of Natural History 81:361-384.

Gilmore, C. W. 1943. Osteology of Upper Cretaceous Lizards from Utah, with a description of a new species. Proceedings of the United States National Museum 93:209-214.

Langer, M. C. 1998. Gilmoreteiidae new family and *Gilmoreteius* new genus (Squamata, Scincomorpha): replacement names for Macrocephalosauridae Sulimski, 1975 and *Macrocephalosaurus* Gilmore, 1943. Comunicações do Museu de Ciências e Technologia da PUCRS. Série Zoologia 11:13-18.

Linnaeus, C. 1758. Systema Naturae, edition X, vol. 1 (Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis. Tomus I. Editio decima, reformata.) Holmiae Salvii, 824 pp.

Marsh, O. 1892. Notice of new reptiles from the Laramie Formation. American Journal of Science 43:449-453.

Norell, M., and K. Gao. 1997. Braincase and phylogenetic relationships of *Estesia mongoliensis* from the Late Cretaceous of the Gobi Desert, and the recognition of a new clade of lizards. American Museum Novitates 3211:1-25.

Nydam, R. 2000. A new taxon of helodermatid-like lizard from the Albian-Cenomanian of Utah. Journal of Vertebrate Paleontology 20: 285.

Nydam, R. 2002. Lizards of the Mussentuchit Local Fauna (Albian-Cenomanian boundary) and comments on the evolution of the Cretaceous lizard fauna of North America. Journal of Vertebrate Paleontology 22:645-660.

Nydam, R., and R. Cifelli. 2002a. A new teiid lizard from the Cedar Mountain Formation (Albian-Cenomanian boundary) of Utah. Journal of Vertebrate Paleontology 22:276-285.

Nydam, R., and R. Cifelli. 2002b. Lizards from the Lower Cretaceous (Aptian-Albian) Antlers and Cloverly Formation. Journal of Vertebrate Paleontology 22:286-298.

Nydam, R., J., Eaton, and J., Sankey. 2007. New taxa of transversely-toothed lizards (Squamata: Scincomorpha) and new information on the evolutionary history of "Teiids". Journal of Vertebrate Paleontology 81:538-549.

Obradovich, J. 1993. A Cretaceous time-scale; pp. 379-396 in W. Caldwell and W. Kauffman (eds.), Evolution of the Western Interior Basin. Geological Association of Canada Special Paper 39.

Oelrich, T. 1956. The anatomy of the head of *Ctenosaura pectinata* (Iguanidae). Miscellaneous Publications, Museum of Zoology, University of Michigan 94: 1–122.

Oppel, M. 1811. Die Ordnungen, Familien, und Gattungen der Reptilien als Prodrom einer Naturgeschichte derselben. J. Lindauer, München, 86 pp.

Prothero D., and R. Estes. 1980. Late Jurassic lizards from Como Bluff, Wyoming and their palaeobiogeographic significance. Nature 286:484-486.

Shukla, U., and R. Srivastava. 2008. Lizard eggs from Upper Cretaceous Lameta Formation of Jabalpur, central India, with interpretation of depositional environments of the nest-bearing horizon. Cretaceous Research 29:674-686.

Sternberg, C. 1951. The lizard *Chamops* from the Wapiti Formation of Northern Alberta: *Polyodontosaurus grandis* not a lizard. Bulletin of the National Museum of Canada 123:256-258.

Sulimski, A. 1972. *Adamisaurus magnidentatus* n. gen., n. sp. (Sauria) from the Upper Cretaceous of Mongolia. Palaeontologia Polonica 27:33-40.

Sulimski, A. 1975. Macrocephalosauridae and Polyglyphanodontidae (Sauria) from the Late Cretaceous of Mongolia. Palaeontologia Polonica 33:25-102.

Tanke, D. 2004. Mosquitoes and mud – The 2003 Royal Tyrrell Museum of Paleontology expedition to the Grande Prairie region (north-western Alberta, Canada). Alberta Paleontological Society Bulletin 19:3-31.

FIGURE CAPTIONS

FIGURE 1. **A,** map of the province of Alberta showing the extension of the Wapiti Formation and the Kleskun Hill Park site, north-west of Grande Prairie. **B**, simplified stratigraphic column showing the occurrence of the Kleskun Hill site within the Western Interior Basin successions of Alberta (marine units in grey).

FIGURE 2. Detailed litholog of the Kleskun Hill Park showing the occurrence of the fossiliferous bentonitc paleosoil. The composite cross-section shows the reciprocal position of the dated volcanic ash bed and the fossiliferous layer. Dashed lines indicate beds used for correlation.

FIGURE 3. *Socognathus unicuspis*; UALVP 50958, Left side of partial skull. **A**, light micrograph. **B**, line drawing of same. **C**, exploded view isolating all visible elements. Scale bar equals 2 mm.

FIGURE 4. *Socognathus unicuspis*; UALVP 50958 same as fig 3. **A**, right side. **B**, SEM of left side in oblique inferior view. **C**, detail of anterior teeth of maxilla. **D**, detail of posterior teeth of maxilla. All scale bars equal1 mm.

FIGURE 5. *Socognathus unicuspis.* **A-D**, UALVP 50960, rostralmost portion of cranium. Anterior view of premaxilla in **A**, light micrograph and. **B**, line drawing of same. Superior view of premaxilla and anteriormost premaxillae in **C**, light micrograph and **D**, line drawing of same. **E-F**, UALVP 50961, anteriormost right maxilla. **E**, light micrograph of lateral view and **F**, line drawing of same. Scale bar equals 2 mm.

FIGURE 6. *Socognathus unicuspis*; UALVP 50963, multi-element block with postcranial elements. **A-C**, two caudal vertebrae in articulation in **A**, ventral view **B**, oblique lateral view, and **C**, cross-sectional view. **D**, detail of haemal arch. Scale bars equal 1 mm.

FIGURE 7. *Kleskunsaurus grandeprairiensis* gen. et sp. nov. UALVP 50959, partial skull. **A**, SEM of left side. **B**, line drawing of same. **C**, exploded view isolating visible portion of each element. Scale equals 2 mm.

FIGURE 8. *Kleskunsaurus grandeprairiensis* gen. et sp. nov. UALVP 50959, partial skull. **A**, light micrograph of right side. **B**, line drawing of same. **C**, exploded view isolating visible portion of each element. Scale bar equals 2 mm.

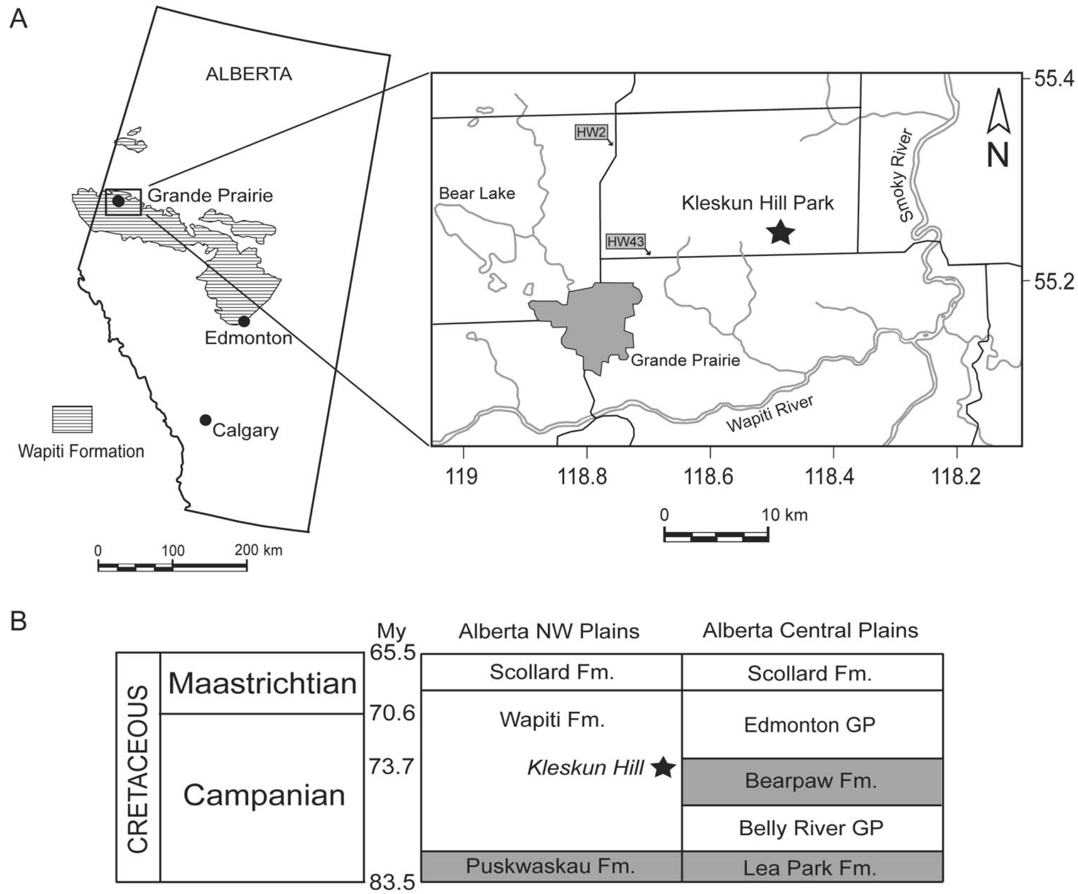

A
ALBERTA
Grande Prairie
Edmonton
Calgary
Wapiti Formation
0
100
200 km
Bear Lake
HW2
HW43
Kleskun Hill Park
Smoky River
N
Grande Prairie
Wapiti River
55.4
55.2
119
118.8
118.6
118.4
118.2
0
10 km
B
My
Alberta NW Plains
Alberta Central Plains
CRETACEOUS
Maastrichtian
Campanian
65.5
70.6
73.7
83.5
Scollard Fm.
Scollard Fm.
Wapiti Fm.
Edmonton GP
Kleskun Hill
Bearpaw Fm.
Belly River GP
Puskwaskau Fm.
Lea Park Fm.

Figure 1

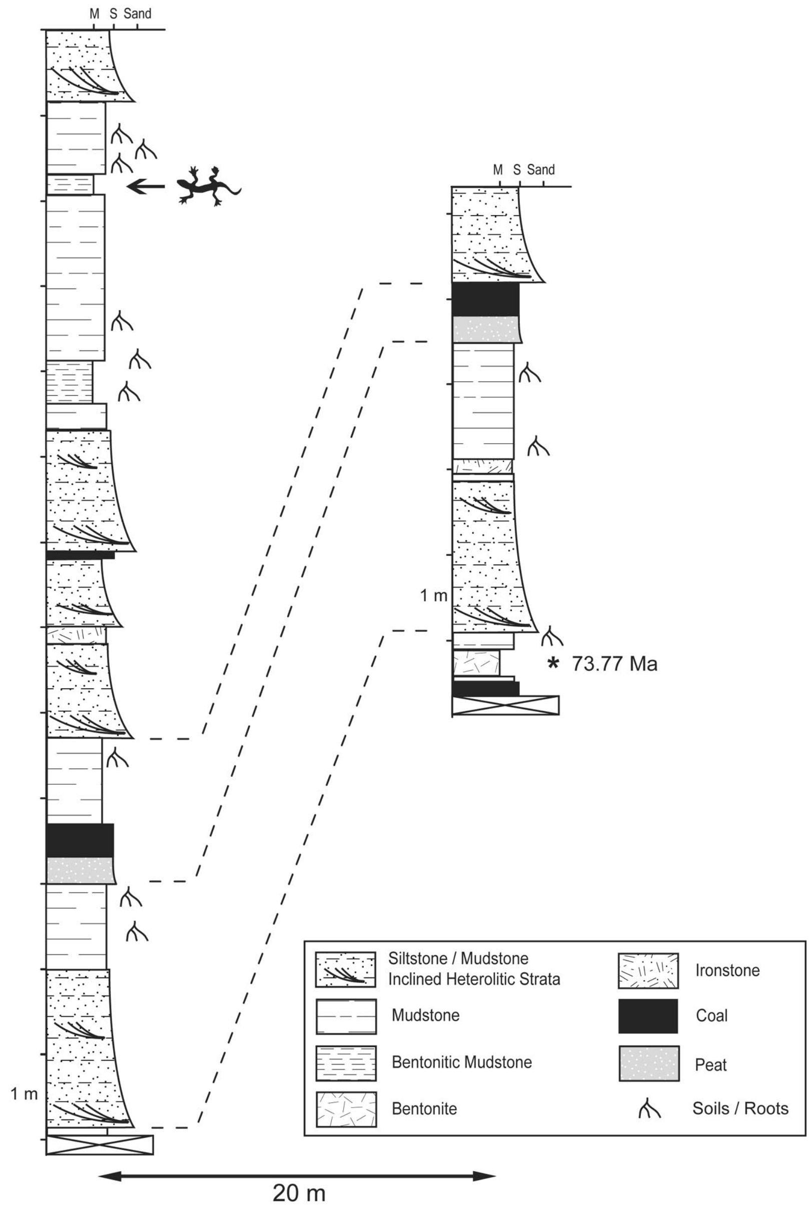

M S Sand
M S Sand
1 m
1 m
* 73.77 Ma
20 m
Siltstone / Mudstone
Inclined Heterolitic Strata
Mudstone
Bentonitic Mudstone
Bentonite
Ironstone
Coal
Peat
Soils / Roots

Figure 2

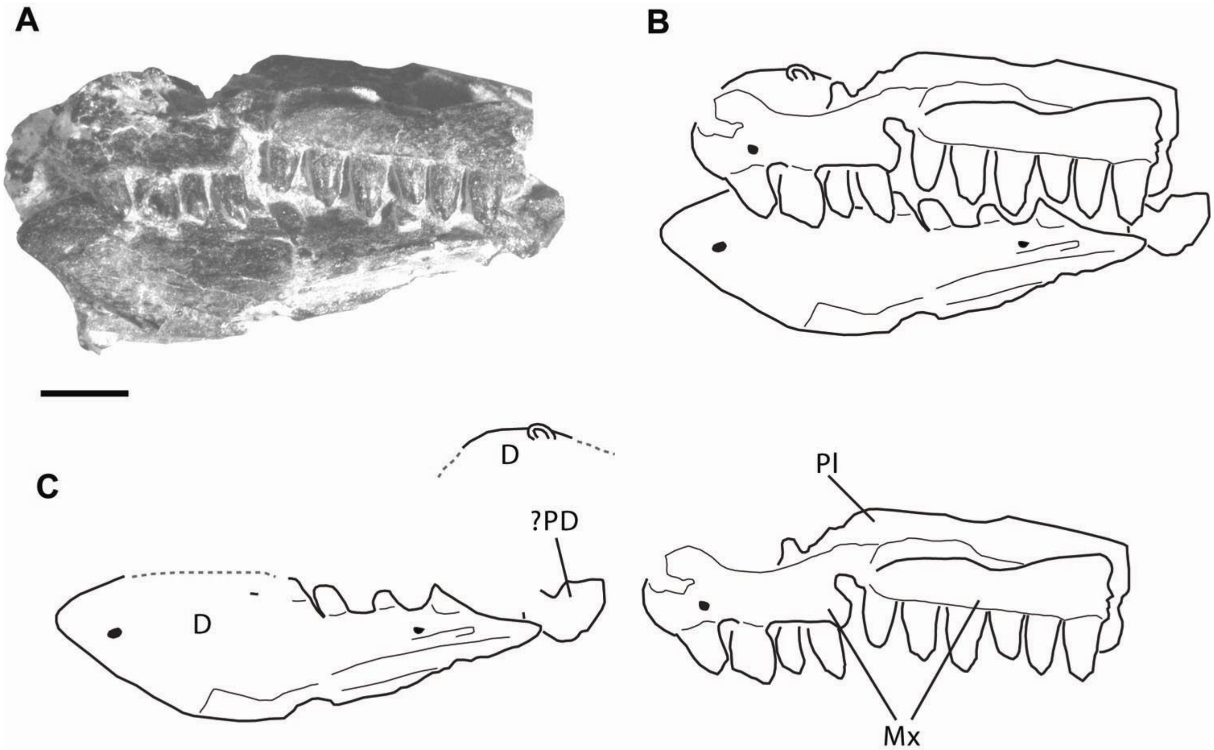


Figure 3

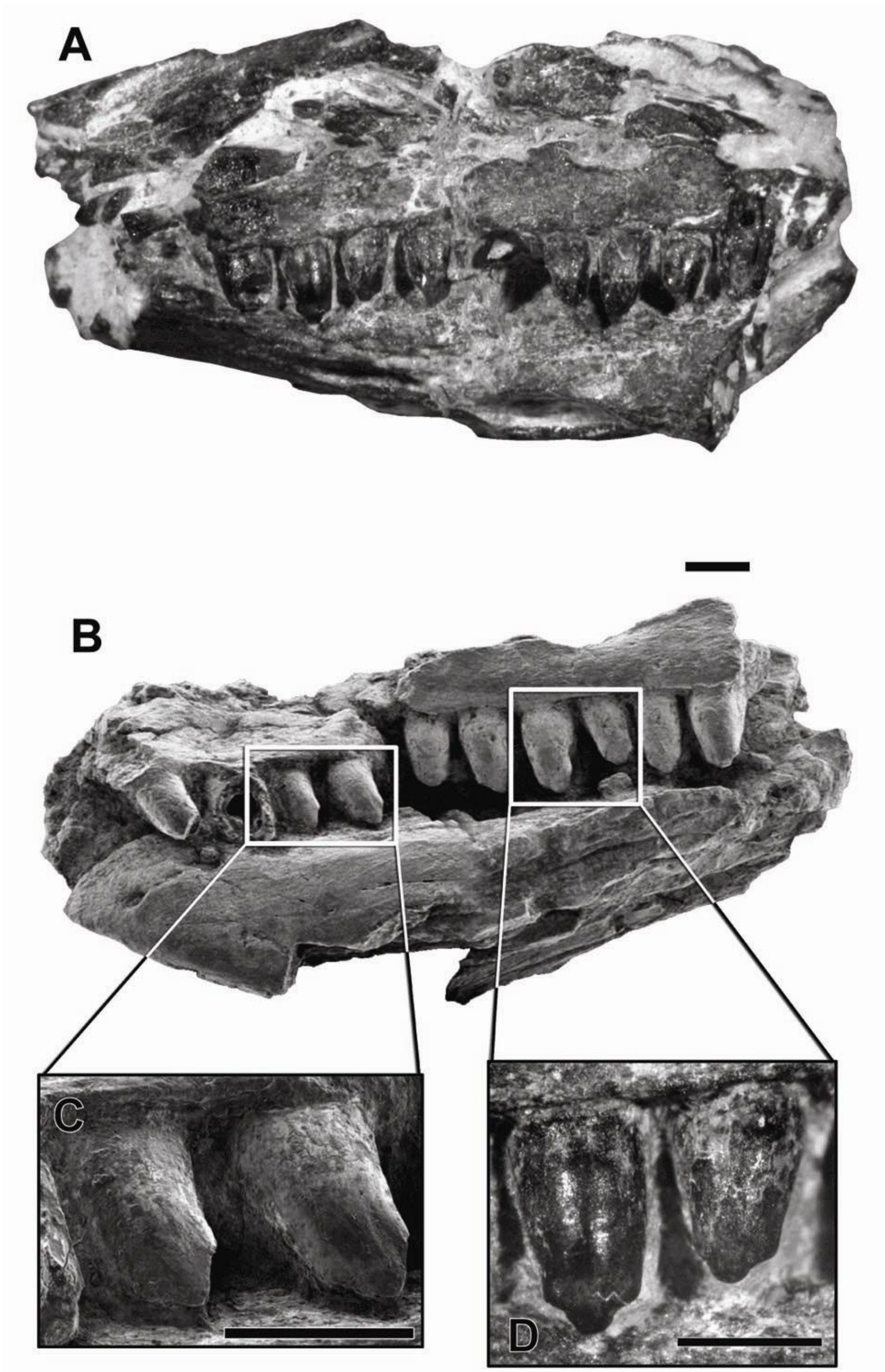


Figure 4

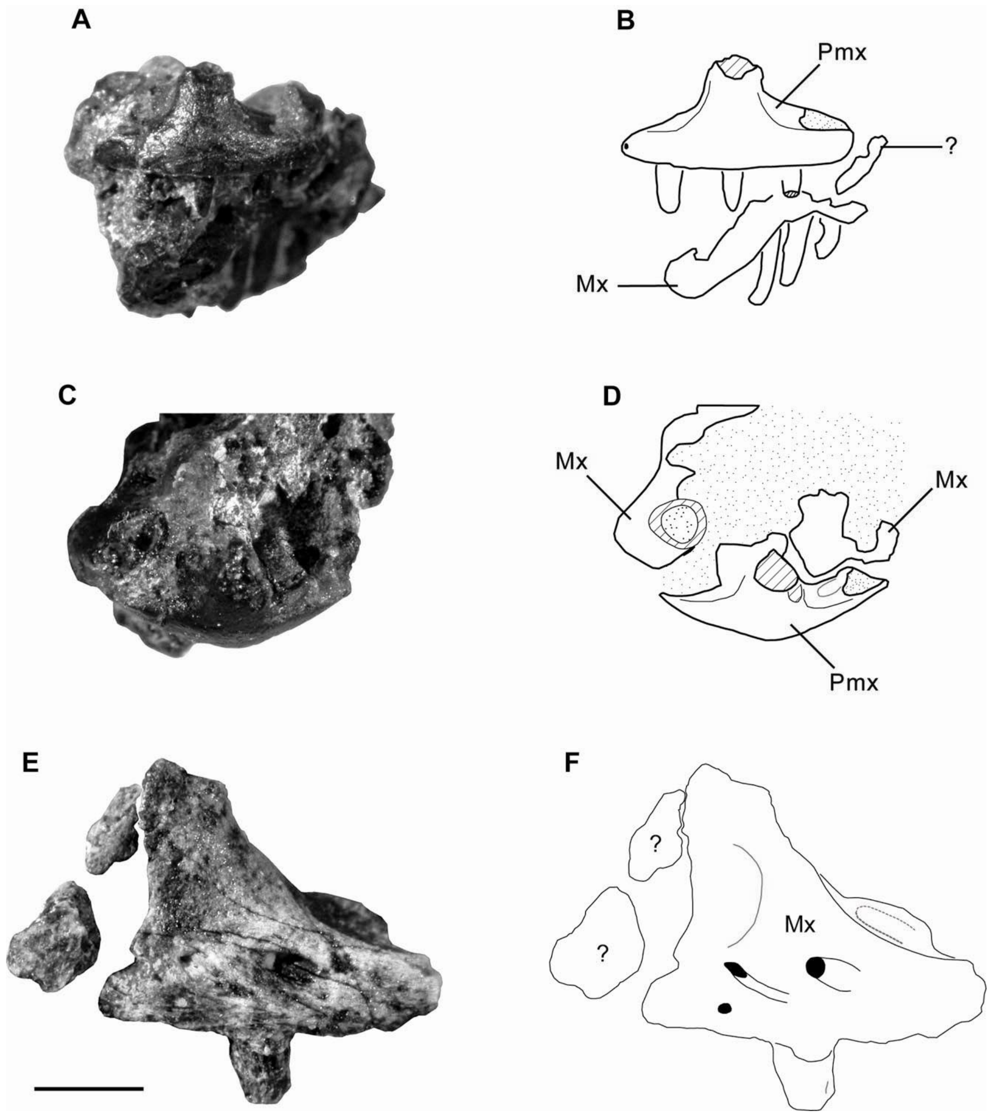


Figure 5

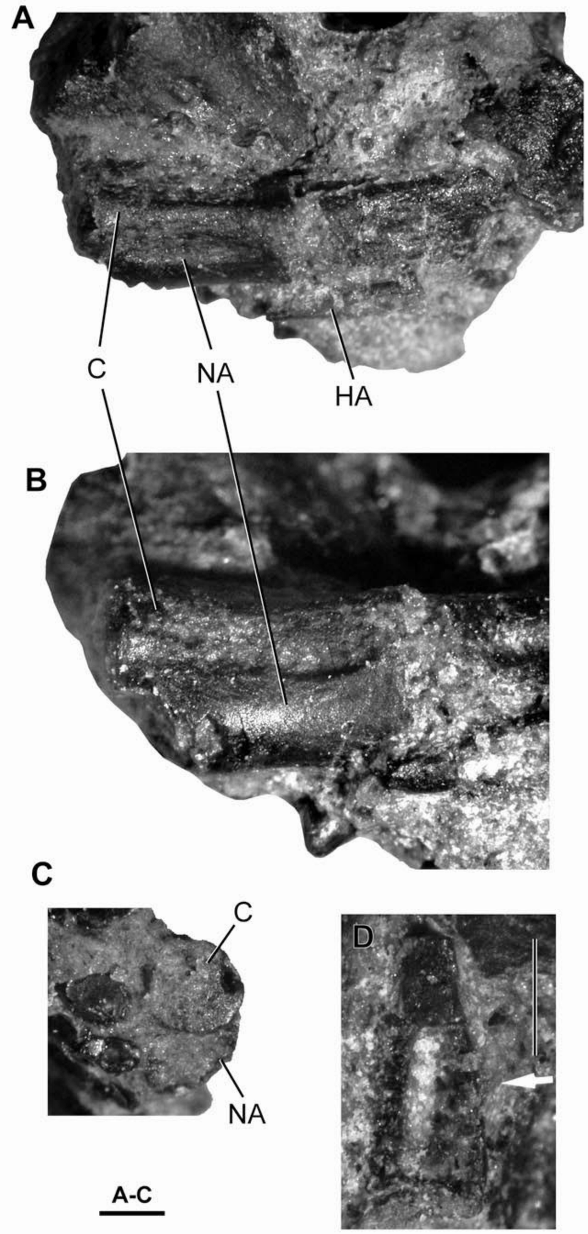


Figure 6

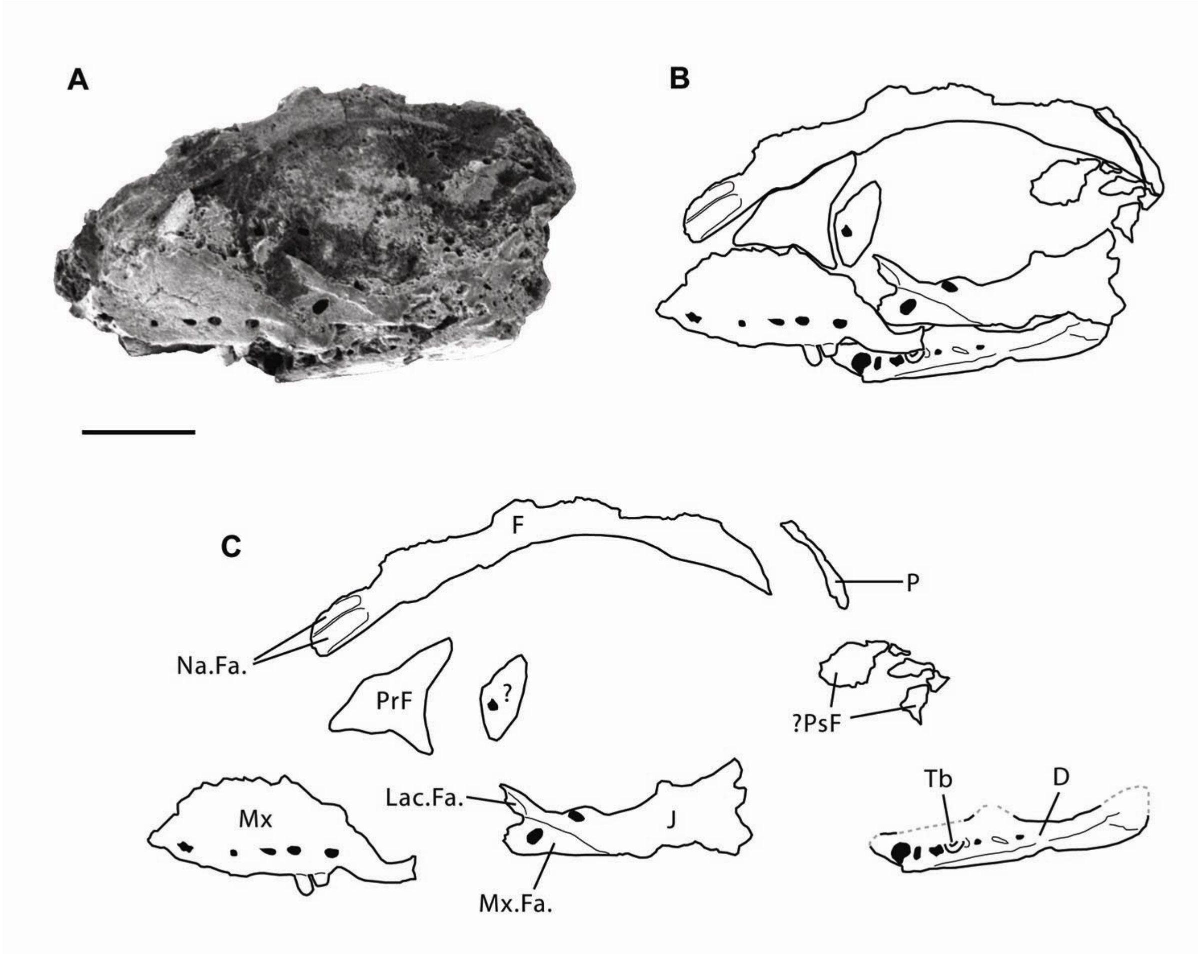


Figure 7

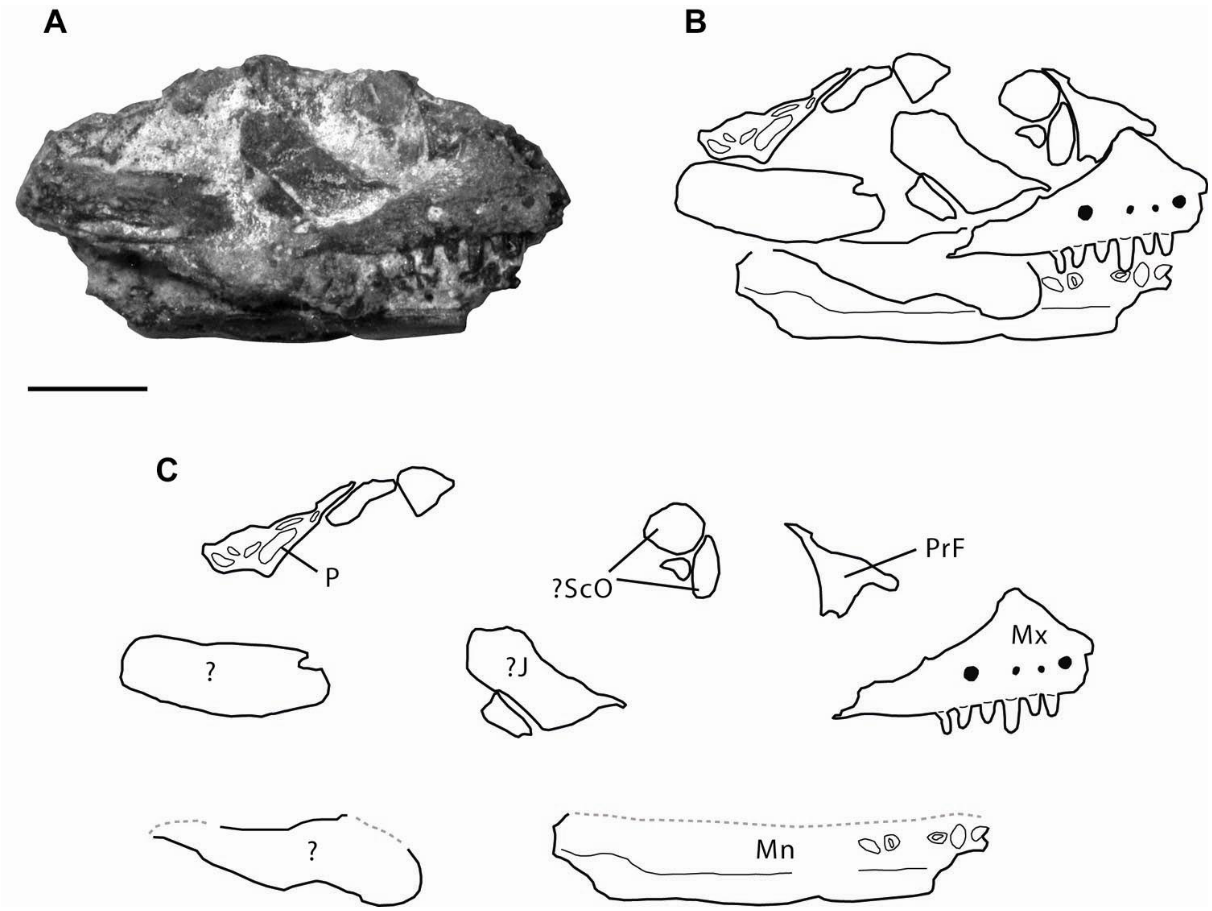


Figure 8

Synthesis

Sedimentology, Geochemistry, Stratigraphy, and Sequence Stratigraphy

Outcrop and subsurface data from the Grande Prairie region in west-central Alberta indicate that the Wapiti Formation can be subdivided into five regionally mappable lithostratigraphic units accumulated during Campanian-Maastrichtian time. These units are separated by both conformable facies contacts and subaerial unconformities of undetermined duration. In ascending order, units 1, 2 and the basal deposits of unit 3 represent different stages of a major progradation of the Wapiti clastic prism during the middle Campanian, followed by a period of increasing accommodation and sediment starvation represented by fine grained deposits of the upper part of unit 3. A second phase of reduced accommodation and increasing sediment supply is represented by units 4 and 5, which are both capped at their tops by a widespread coal zone (the Red Willow and Cutbank Coal Zones, respectively).

Volcanic ash beds are frequently interbedded with fluvial deposits of the Wapiti Formation. Their stratigraphic occurrence and distribution suggest restricted time intervals (< 1Ma) of intense eruptive activity in the Cordillera volcanic centers, particularly in concomitance with the Bearpaw seaway transgressive and regressive phases, and in the uppermost deposits of the Wapiti Formation (lower Maastrichtian). Geochemical analyses suggest the presence of multiple source areas with different tectonic setting and magmatic composition that resulted in a peculiar bimodal occurrence of basic and acidic volcanic ashes. The presence of regionally extensive volcanic ash bed that can be confidentially traced in both outcrop and subsurface provide excellent tools for intra- and inter-formational correlations.

From a sequence stratigraphic point of view, the Wapiti Formation consists of four unconformity-bounded depositional sequences: in ascending order, sequence 1 marks the transition from the underlying marine facies of the Puskwaskau Formation to the Wapiti fluvial facies, and consists of strongly progradational and aggradational (high accommodation) deposits. Sequences 2 and 3 consist of amalgamated channel-fill deposits at the base (low accommodation), which grade upwards into more floodplain-dominated successions (high accommodation). Sequence 4 is dominated by channel sediments and extensive overbank facies, indicating high accommodation and an overall trend of vertical aggradation. Furthermore, the identification of maximum flooding surfaces (MFS) associated to regionally extensive coals that accumulated at more the 200 km from the coeval shoreline, support the utility of coal seams as genetic stratigraphic sequence boundaries in non-marine successions.

With respect to the timing of deposition and overall stratigraphic architecture, the proposed subdivisions of the Wapiti Formation share many similarities with the well-studied Belly River and Edmonton Groups of central and southern Alberta. Differences lie primarily in the proximal deposits not affected by coastal, estuarine or paralic deposition derived from base level oscillations. Tectono-sedimentary relationships in the northern section of the Cordillera and adjacent basins were characterized by intermittent thrust loading of the basin margin, long periods of isostatic rebound, subsequent cannibalization, and widespread southwestward dispersal of foredeep sediments. Major shifts from lower to higher sinuosity fluvial systems as well as the intercalation of fine and coarse fluvial sediments also suggest variations of the depositional slope within the basin. During active loading and thrusting, coarse clastics accumulated in the foredeep and thus, sedimentation of finer grained facies, as well as intervals of sediment starvation, characterize the distal section of the basin.

Paleontology

Investigating the paleontological resources of the Wapiti Formation is essential because this succession represents a long interval of continuous terrestrial sedimentation that records a critical time period in dinosaur and other vertebrate evolution (including mammals, amphibians, and birds). In the last decade, field activities in the Grande Prairie region have resulted in the discoveries of several important fossil localities, some among the richest ever found in Alberta and North America. These include ceratopsian-dominated bonebeds, dinosaur skeletons, isolated teeth and bones ascribed to tyrannosaurs, troodontids and ankylosaurs, microvertebrate sites, trackway localities, insects in amber, and megaplant fossils. Of particular relevance are 1) hatchling- to nestling-sized hadrosaur elements and *Troodon* teeth suggesting the presence of a hadrosaurid nesting ground (the northernmost occurrence known to date) in lowland areas within the alluvial plain and predator-prey association between juvenile hadrosaurids and *Troodon*; 2) articulated cranial material of and a new taxon of scincomorph lizard (*Kleskunsaurus grandepraireinsis*) that represent the northernmost occurrence of fossil lizards in North America; 3) a new species of the horned dinosaur *Pachyrhinosaurus* that presents anatomical characters, including larger body size and nasal bosses that contact the supraorbital bosses, that suggest it can be identified as closely related to *Pachyrhinosaurus canadensis* previously reported from Alaska and southern Alberta.

With an uninterrupted latest Cretaceous terrestrial record, the Wapiti Formation offers a unique look into the mode and tempo of the evolution of a variety of taxa. Furthermore, the Wapiti fossil record is geographically important, as the locality is between the mid-latitude deposits of southern Alberta and the high-latitude fossil localities of Alaska. As such, further paleontological studies on the Wapiti Formation will reveal the nature of the transitional faunas between southern Alberta and Alaska, which can shed light into migratory, evolutionary, and biogeographic aspects of vertebrate distribution in North America at the end of the Cretaceous.

Appendixes

Horned Dinosaur Symposium – Drumheller 2007

A new *Pachyrhinosaurus* bonebed from the late Cretaceous Wapiti Formation

Federico Fanti* and Philip J. Currie**

*University of Bologna

Department of Earth and Geoenvironmental Sciences

Via Zamboni 67, I-40127 Bologna, Italy

Email: federico.fanti@unibo.it

** University of Alberta

Department of Biological Sciences

CW405 Biological Sciences Building

Edmonton, Alberta T6G 2E9, Canada

Email: Philip.currie@ualberta.ca

In the last decade, field activities in the Grande Prairie region have resulted in the discoveries of several important fossil localities, some among the richest ever found in Alberta and North America. These include ceratopsian-dominated bonebeds, dinosaur skeletons, isolated teeth and bones ascribed to tyrannosaurs, troodontids and ankylosaurs, microvertebrate sites, trackway localities, insects in amber, and megaplant fossils. In spite of these discoveries, there have been relatively few reports (Allan and Carr, 1946; Stott, 1961; Dawson et al., 1994; Tanke, 2004, 2006; Currie et al., in press), and the geological and palaeontological importance of the Wapiti Formation remains virtually unknown. Among tens of important fossiliferous localities, two vast and rich ceratopsian bonebeds play the most important role in the Wapiti Formation paleontological record.

Known since 1975, the Pipestone Creek *Pachyrhinosaurus* bonebed (Fig. 1) is 800 meters upstream from its confluence with the Wapiti River, and is less than 25 km SW of the city of Grande Prairie. With more than 99% of the recovered material ascribed to ceratopsian dinosaurs and an extremely high abundance of well preserved bones (up to 200 elements per square meter), this fossil assemblage represents the richest ceratopsian bonebed ever found in North America (Tanke, 2006; Currie et al., in press). Caused by an unknown catastrophic event, it preserves a monospecific taphocenosis, and thus is similar to several large horned dinosaur bonebeds from southern Alberta. Even though only 52 square meters of the bonebed have been excavated to date, exploration borehole cores show the bonebed extends for at least 70 linear meters (Geo-Engineering, 2005; Graber and Hunt, 2006). At the excavation site, the source layer is more than 50 meters wide, suggesting the bonebed covers more than 3,500 square meters. The bonebed has also been identified 120 metres downstream on the opposite side of Pipestone Creek, so this estimate is in fact conservative. If we assume that there are 150 bones per square metre on average, and that there are 288 skeletal elements in a ceratopsid dinosaur (Ryan et al. 2001), we obtain an estimate of 1800 individuals involved in the depositional event. Bone density within a single bonebed varies greatly (Eberth and Getty, 2005), but even reducing the average to 50 bones per square meter, we still obtain the impressive value of more than 600 individuals. Another way to estimate the number of ceratopsian individuals is to take the number of skulls (15 adult skulls according to Currie et al., in press) excavated in 52 square metres, and extrapolate to the whole bonebed area. This produces an estimate of more than 1,000 individuals for the bonebed. Although excavation and subsequent analysis is the only way to reliably establish a minimum number of individuals, our estimates do suggest that an impressive number of dead animals are represented in the Pipestone Creek bonebed. Age/size distribution of the animals in the bonebed is just one line of evidence that suggests that the death of these animals was catastrophic, rather than attritional (Currie et al., in press).

Large amounts of coalified plant fragments within the bonebed matrix at Pipestone Creek, and the almost complete disarticulation of skeletal remains, which often have trampling traces, indicate a complex taphonomic pre-burial history that included subaerial exposure in a wet, pond-like environment, transportation and final burial of highly reworked elements. In addition, orientation measurements on fossil elements (>15 cm) within a section of the bonebed (n=102) show significant multi-modal distribution indicating consistent syn-depositional hydraulic reworking at the site. Because of the complex taphonomic history at the site, we may never know the genesis of the catastrophic event..

A composite geological section, obtained by combining data from four borehole cores (PC1 - 4) and sedimentological analysis at the site, reveals that the Pipestone Creek bonebed lies within a 2.5 to 4 metre thick, laterally continuous, carbonaceous, dark grey, organic-fragment-rich siltstone layer (Fig. 2). Vertical facies alternation is typical of levee to overbank deposits, with interbedded fining upward sequences bounded by sharp erosional surfaces. At the top of the overbank deposits are paleosols, interbedded amber-rich coal seams, and soft, light green to yellow bentonites. Carbonaceous nodules as well as clay lenses are also present. The same stratigraphic architecture, with a more significant sandstone composition, can be observed in several outcrops downstream along Pipestone Creek and along nearby sections of the Wapiti River. Hadrosaur and isolated ceratopsian remains have been collected near the mouth of the creek. Thick, low-angle ripples within the sandstone layers underlying the bonebed indicate a high-energy environment and a high sediment supply: paleocurrent measurements (n=23) indicate a flow direction from southwest to northeast (N35°E). This is also compatible with the progressive thickening of the fossiliferous siltstone layer and concomitant pinching out of the basal sandstone toward the north. A volcanic ash located 28 meters above the bonebed level yielded an age of 73.25 ± 0.25 My (Eberth in Currie et al., in press), roughly equivalent to the maximum transgression of the Bearpaw Sea in central and southern Alberta (*Baculites compressus* zone). Measured sections combined with palynological and radiometric data suggest that this section of the Wapiti Formation has an average sediment accumulation rate between 7.5 and 9 cm / 1000 yrs, compatible with a condition of increasing accommodation (TST or HST) that has also been observed in the lower Horseshoe Canyon Formation in central Alberta (Eberth, 2002). This interpretation is consistent with the presence of large bonebeds and isolated fossil remains in overbank settings. Fossil remains recovered from the site have been identified as a new species of *Pachyrhinosaurus* (Currie et al., in press).

The Wapiti River bonebed occurs on top of a widespread, slumped exposure on the north side of the Wapiti River, approximately 32 km upstream from the mouth of Pipestone Creek. This site has been known locally for many years, and has been visited by many generations of school classes

(Bert Hunt, pers. comm., 2007). Most of a skull (TMP 2001.11.1) was excavated in 2001 by a field party from the Royal Tyrrell Museum of Palaeontology. Although it was collected from high on the wall of the slumped area, it was uncertain whether the specimen was recovered from the *in situ* layer, or was in a large slump block. A nine square metre excavation was undertaken by a University of Alberta field party in 2007, who also traced the bonebed at the same level for 107 linear metres. So far, a minimum number of eight individuals have been identified by the recovery of partial adult skulls (in the collections of the Tyrrell Museum and the University of Alberta) that include their nasal bosses. Although it is conceivable that the entire face of the bonebed has slumped below its original level in the bedrock, it now seems more likely that the bone from this level has slumped little, if any. Weathering and erosive processes are particularly intense on the slope surface, and larger fossil remains, including skulls, slump downhill onto the floodplain of the Wapiti River. Fragmentary and well preserved but small dinosaur remains litter the slope surface. Excavation revealed a lower density of bone than recovered in the Pipestone Creek bonebed (Fig. 3A), and there seems to be 30 to 50 bones per square metre. Teeth and small fragments of ribs and ossified tendons are mixed with partial skulls (including the fused snouts, bosses and circumorbital regions of mature animals), vertebrae and limb elements. Overall, bone fragments recovered are smaller on average than those from the Pipestone Creek bonebed, suggesting there was a different pre-burial history. Although all identifiable bones are ceratopsian, teeth of a tyrannosaur and *Troodon* have also been recovered from the quarry. Finally, specimens collected preserve an almost undistorted three-dimensional shape indicating that the bonebed was less affected by load or shape deformation than the Pipestone Creek bonebed. Most of the larger bones, including the nasal bosses, are encased within ironstone nodules, whereas smaller bones can be found in either the poorly consolidated mudstones or within the ironstone nodules.

The Wapiti River bonebed (Fig. 3B) is associated with a persistent but less than half a meter thick, organic-rich mudstone layer with abundant ironstone nodules. It lies on top of a 150 cm thick organic-fragment-rich, dark grey silt with laminar tractive structures. In addition, well developed "wet" and immature paleosols in close association with coal lenses, thin ironstone layers, and minor clay lenses are frequently interbedded above and below the bonebed. Discontinuous sandstone layers and the massive presence of overbank facies suggest a depositional environment similar to the one described for the Pipestone Creek bonebed. A 15 cm thick, light green volcanic ash has been sampled 180 cm below the bonebed layer, and is now being processed using standard radiometric dating techniques. The presence of the palynomorph *Wodehouseia edmontonicola* in the deposits overlying the bonebed has been used for dating because of its restricted age range (from 70.5 to 71.8 Ma). However, it should be noted that the stratigraphic range of this species may extend from the upper Bearpaw Formation to the top of the Horseshoe Canyon Formation, which would give it a time range between roughly 67 and 74 My (Dennis Braman, pers. comm., 2007).

Geophysical data from three gas wells close to the Wapiti River site and outcrop measurements have been used to produce composite geological sections showing that the bonebed is approximately 605 metres above the base of the Wapiti Formation. Therefore, the Wapiti River bonebed is higher than the Red Willow Coal Zone. In contrast, the Pipestone Creek bonebed is about 435 metres above the base of the Wapiti Formation, well below the Red Willow Coal Zone (Dawson et al., 1994). Although both bonebeds occur within thick intervals of overbank deposits that accumulated under high accommodation conditions, they are different in that the Wapiti River site anomalously lacks sandstone deposits below the fossiliferous layer for no less than 5 meters. The Red Willow Coal Zone in the area marks a major environmental shift, which is also supported by the presence of extremely abundant organic material and well developed paleosols within fluvial deposits higher in the section above the coal zone. Palynological data from the coal seams to indicate a latest Campanian to early Maastrichtian age (Dawson et al., 1994). This is consistent with changes in the depositional style observed in the transition between units 1 and 2 within the Horseshoe Canyon Formation, reflective of the "*Drumheller Marine Tongue*" transgressive event at 70.5 My (Eberth, 2002; Eberth and Deino, 2005). Despite the fact that the altitude of the Wapiti River Bonebed is 100 meters higher than the Pipestone Creek Bonebed, composite cross sections suggest that the bonebeds are in fact separated by about 170 meters of rock. The depositional style suggests a medium to high vertical aggradation rate. Using an average sediment accumulation rate of 6 cm / 1000 yrs, the 170 meters would represent 2.83 My. This would suggest that the Wapiti River bonebed is approximately 70.4 million years old, which would make the fossils it contains coeval with the type species of *Pachyrhinosaurus canadensis* from southern Alberta. Not surprisingly, the specimens in the Wapiti River bonebed have anatomical characters, including larger body size and nasal bosses that contact the supraorbital bosses, that suggest it can be identified as *Pachyrhinosaurus canadensis*, rather than as the *Pachyrhinosaurus* species represented at the Pipestone Creek bonebed (Currie et al., in press).

References:

Allan, J., and Carr, J. 1946. Geology and coal occurrences of Wapiti-Cutbank area, Alberta. Research Council of Alberta Report 48, 50 pp.

Dawson, F., Kalkreuth, W., and Sweet, A. 1994. Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta. Geological Survey of Canada Bulletin 466, 60 pp.

Eberth, D. 2002. Review and comparison of Belly River Group and Edmonton Group stratigraphy and stratigraphic architecture in the southern Alberta plains. CSPG Diamond Jubilee Convention, Program and Abstracts 117. Abstracts of Technical Talks, Poster & Core Displays including Extended Abstracts. PDF file 227S0125. Compact Disc.

Eberth. D., and Deino, A. 2005. New 40Ar/39Ar ages from three bentonites in the Bearpaw, Horseshoe Canyon, and Scollard formations (Upper Cretaceous-Paleocene) of southern Alberta. *In* Dinosaur Park Symposium – Short Papers, Abstracts, and Program. Special Publication of the Royal Tyrrell Museum. *Edited by* D. Braman, F. Therrien, E. Koppelhus, and W. Taylor, pp 23-24.

Eberth, D., and Getty, M. 2005. Ceratopsian bonebeds: occurrence, origins, and significance. *In* Dinosaur Provincial Park, a spectacular ancient ecosystem revealed. *Edited by* P. Currie and E. Koppelhus. Indiana University Press, Bloomington, pp 501-536.

Geo-Engineering (M.S.T.) Ltd, 2005. Pipestone Creek Interpretive Centre, phase I, geotechnical investigation. Unpublished report (14 pages) submitted to the County of Grande Prairie, and available on line at WWW.gprc.ab.ca/community/pipestone/3227%20R02%Phase%20I%20-%20Investigation%20Report%20(1).pdf.

Graber, S., and Hunt, B. 2006. Palaeontological Society of the Peace (PSP). *In* Alberta Palaeontological Society, Tenth Annual Symposium. Edited by Howard Allen. Alberta Palaeontological Society, Calgary, pp. 28-29.

Stott, D. 1961. Dawson Creek map area, British Columbia. Geological Survey of Canada Paper 61, 10 pp.

Tanke, D. 2004. Mosquitoes and mud – the 2003 Royal Tyrrell Museum of Paleontology expedition to the Grande Prairie region(north western Alberta, Canada). Alberta Paleontological Society Bulletin, **19**(2): 3-31.

Tanke, D. 2006. Sixty years of Pachyrhinosaur (Dinosauria: Ceratopsidae) discoveries in North America. Alberta Paleontological Society, Tenth Annual Symposium Abstract: 38-56.

Figure Caption:

Fig. 1. Section of the Pachyrhinosaurus n. sp. bonebed at Pipestone Creek (after Currie et al., in press).

Fig. 2. Stratigraphic columns for the bonreholes associated with the Pipestone Creek Bonebed.

Fig. 3. A, quarry map of the Wapiti River Bonebed, showing the size and distribution of bone excavated in the test excavation by the University of Alberta in 2007. B, stratigraphic column of the beds in the vicinity of the Wapiti River Bonebed.

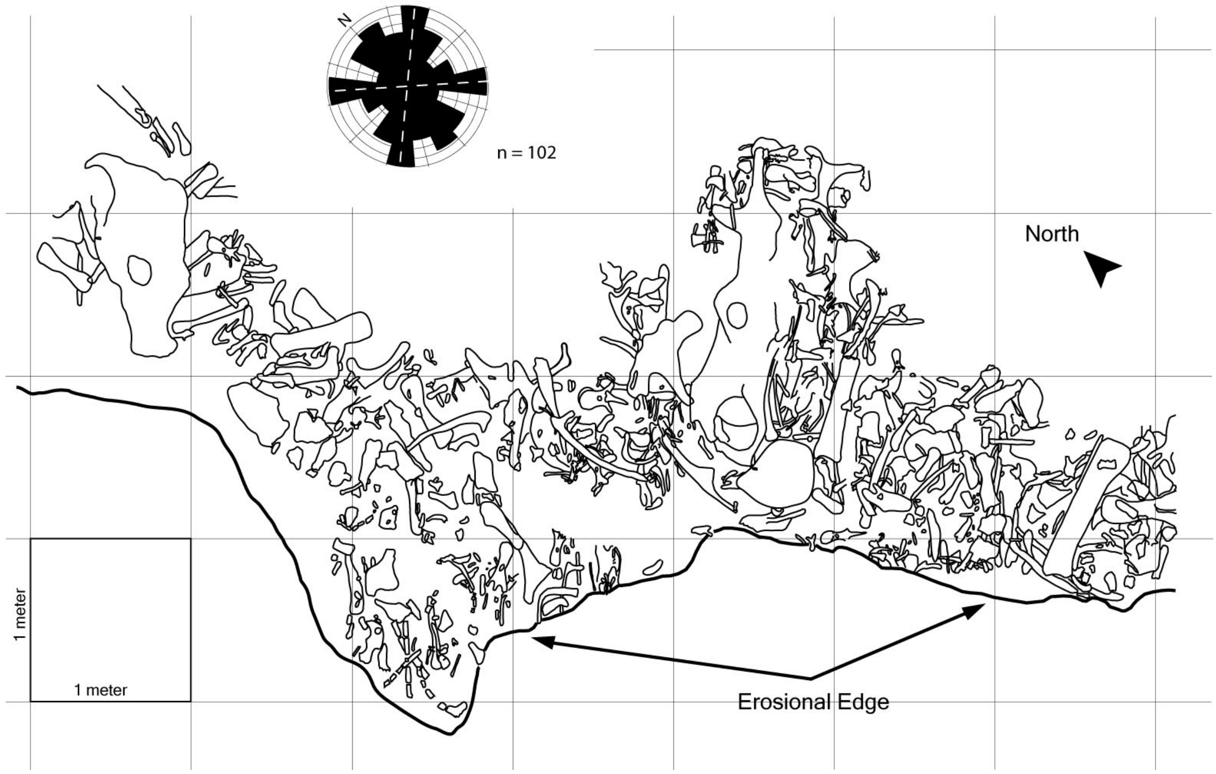
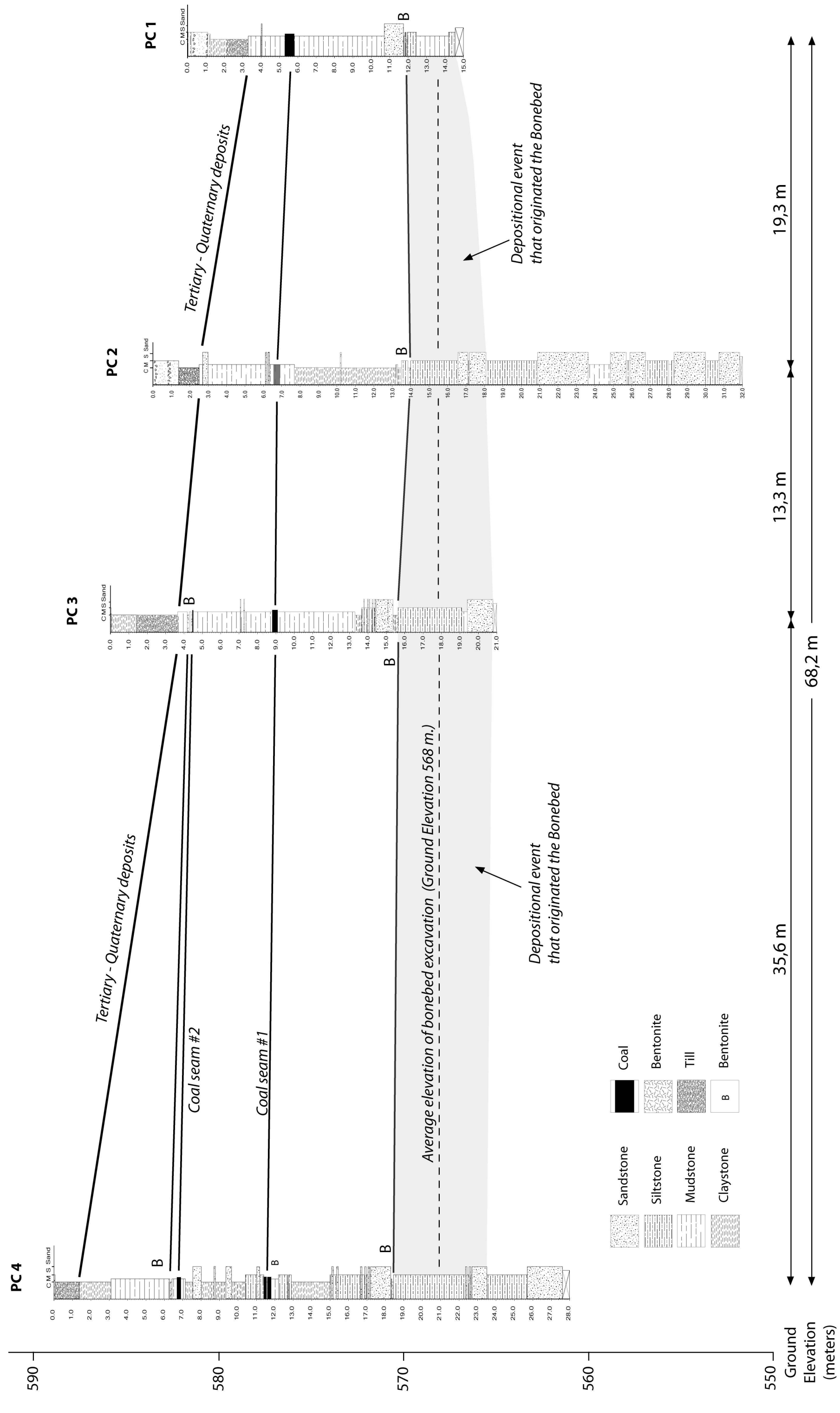


Figure 1



PC 1
PC 2
PC 3
PC 4
Tertiary - Quaternary deposits
Coal seam #2
Coal seam #1
Average elevation of bonebed excavation (Ground Elevation 568 m.)
Depositional event that originated the Bonebed
19,3 m
13,3 m
35,6 m
68,2 m
Ground Elevation (meters)
Sandstone
Siltstone
Mudstone
Claystone
Coal
Bentonite
Till
Bentonite

Figure 2

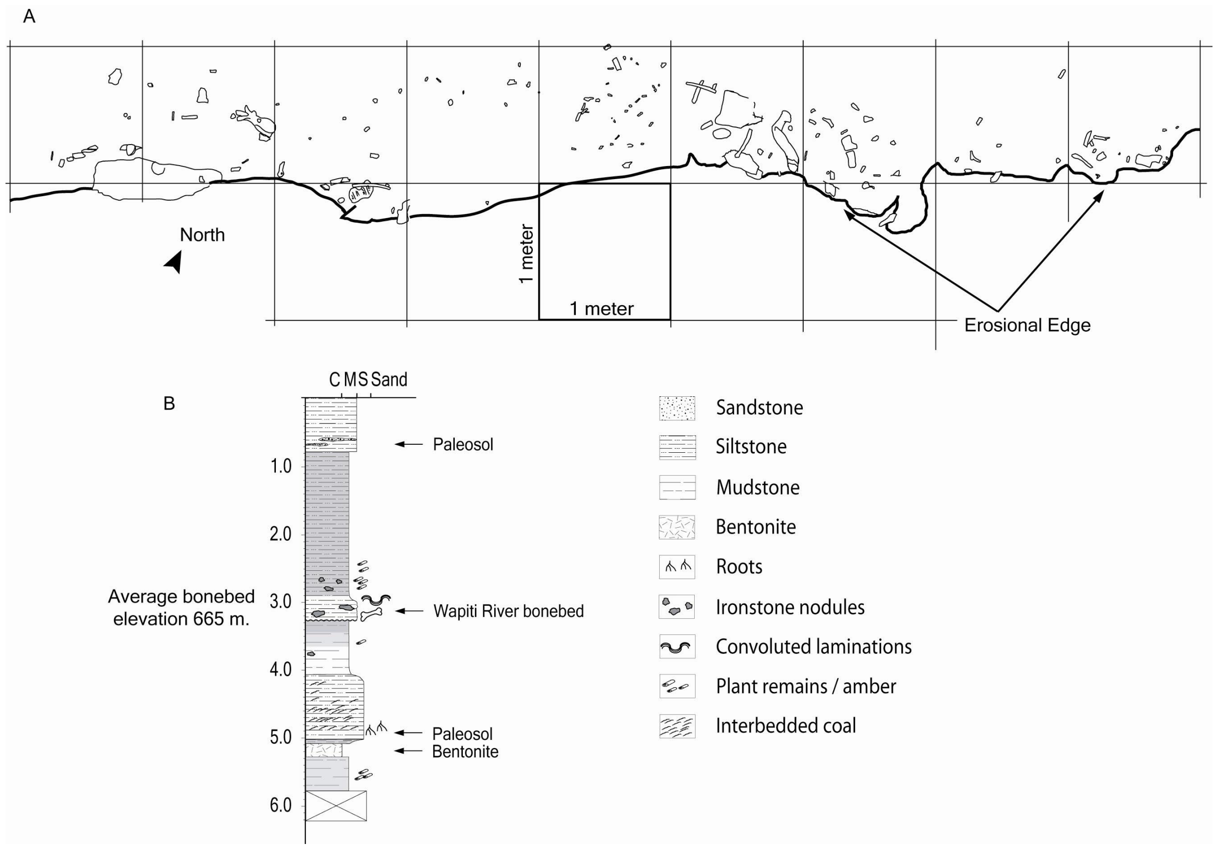

A
North
1 meter
1 meter
Erosional Edge
B
C M S Sand
1.0
2.0
3.0
4.0
5.0
6.0
Paleosol
Average bonebed elevation 665 m.
Wapiti River bonebed
Paleosol
Bentonite
Sandstone
Siltstone
Mudstone
Bentonite
Roots
Ironstone nodules
Convoluted laminations
Plant remains / amber
Interbedded coal

Figure 3

Horned Dinosaur Symposium – Drumheller 2007

Unfolding the geological history of the North: new comprehensive survey of the Wapiti Formation, Alberta, Canada

Federico Fanti

Department of Earth and Geoenvironmental Sciences, University of Bologna,Via Zamboni 67, I-40127 Bologna, Italy

Email: federico.fanti@unibo.it

The Wapiti Formation, which outcrops extensively in northwestern Alberta and northeastern British Columbia, is a sedimentary succession that represents a time interval from lower Campanian to upper Maastrichtian. As such, it is temporally equivalent to the Belly River Group (Foremost, Oldman, and Dinosaur Park formations), the Bearpaw Formation, and the Edmonton Group (Horseshoe Canyon, Whitemud, and Battle formations) of southern and central Alberta, all known for their abundance of fossil vertebrates and high diversity of dinosaur taxa. Moreover, because of its great temporal extent, the Wapiti Formation is contemporaneous with several late Cretaceous deposits elsewhere in North America: the Prince Creek Formation (Alaska), Mesa Verde Formation (Wyoming), the Two Medicine and Judith River formations of Montana, Price Creek and North Horn formations of Utah, and the Fruitland, Kirtland, and Ojo Alamo formations of New Mexico (Denver Fowler, personal communication, 2007). Lacking any marine depositional event, the Wapiti Formation plays a unique role in the western margin of the Western Interior seaway stratigraphic evolution as well as in dinosaur dispersal and paleobiogeography. However, despite these important premises, the Wapiti Formation has been only partially studied because of factors such as remoteness, vast extent of outcrops, vegetation cover, and operational costs.

The study area to date encompasses approximately 22,000 square km in Grande Prairie County in north-western Alberta. In the absence of any previous studies on the stratigraphy and sedimentology of this succession, several approaches (including sequence stratigraphy, geophysics, geochemistry, facies analysis, and palynology) were combined in order to document the entire Wapiti succession in detail, and to correlate regional units to age equivalent deposits elsewhere. Data collected from 548 well logs, combined with outcrop investigation at more than 80 different localities, result in a preliminary analysis of approximately 800 meters of the Wapiti Formation. In addition, fourteen bentonites, some up to 97 cm thick, have been sampled. Six sub-units are identified and correlated with age equivalent deposits of central and southern Alberta, and Alaska. Analysis of the units 1, 3, 4, and 5 resulted from both subsurface and outcrop data, whereas description of units 2A and 2B reflects mostly gamma-ray well log interpretation. Finally, to better characterize the identification of different units, well 07-27-068-11W6 was chosen as the reference for this study (Figure 1).

Unit 1: the basal unit reflects the early basinward progradation of the Wapiti clastic prism in the lower Campanian. The transition from the underlying marine Puskwaskau Formation (Smoky Group) is marked by a gradual coarsening up sequence with up to 30 meter thick shoreface deposits at the top. Exposures along the Smoky River north-west of Grande Prairie represent the complete transition from offshore to shoreface deposits, and currently represent the reference area for the base of the Wapiti Formation. A thick coal layer that outcrops along the Smoky River has been identified in well logs in the entire study area, and marks the base of the overlying coastal plain facies. Fine to medium-grained flood plain deposits with isolated channel sandstones and persistently thick coal seams indicate medium to high accommodation. Facies analysis suggests that sediments were deposited in water-saturated environments, such as organic-rich marshes or ponds. The total thickness of unit 1 at the reference well log locality is 120 meters.

Unit 2A: the transition from unit 1 to the overlying unit 2A is marked by the first appearance of large channel sandstone deposits within alluvial plain facies. It consists of major and minor fluvial distributaries (the individual channel-fill sequence ranges in thickness from 5 to 15 meters), extensive overbank strata, and interbedded tabular coal seams. This unit is also characterized by the presence of a bentonitic marker bed, named Horizon A, which is approximately 20 meters below the top of the unit. The thickness of Unit 2A is 80 meters.

Unit 2B: The lower portion of unit 2B consists of massive, amalgamated, decametre-thick (up to 40 meters) sandstone bodies. These channel deposits usually have sharp erosional bases, while overbank facies at the top of fining up cycles are lenticular and notably lack coal seams. The lower deposits of unit 2B are interpreted as refection of the maximum basinward progradation of the Wapiti Formation before the Bearpaw seaway transgression. The upper portion that conformably overlies the sandy zone, comprises muddy and coaly crevasse splays and overbank deposits, suggesting a significant shift in the depositional style. Thus, the upper deposit of Unit 2B can be correlated with the early transgression of the Bearpaw Sea (Transgressive System Tract conditions). The total thickness of this unit is approximately 60 meters.

Unit 3: The base of unit 3 is easily recognized in both well logs and outcrops by a strong increase in gamma ray response (a significant shift toward the right) and variation in depositional style. A consistent reduction in sandstone bed thickness is associated with silt-mud dominated, inclined heterolitic-strata, as well as tabular and laterally continuous coal seams in association with well developed paleosols. Bedforms usually have lateral-accretion surfaces typical of point bars or lateral bars within the channel. The upper deposits of the bars are extremely rich in organic components, suggesting an origin related to river avulsion, possibly by neck cut-off of meander bends. Two marker beds are identified within this unit: in ascending order, bentonitic layers, Horizons B and C, extend laterally for more than 120 km in the region, although they are occasionally interrupted by erosional channel surfaces. A volcanic ash layer collected in the Kleskun Hills area, where deposits of unit 3 outcrop extensively, yielded an age of 73.77 ± 1.46 My (David Eberth, personal communication, 2006), suggesting that the entire unit 3 is contemporaneous to the Bearpaw Formation. Thus, the marked change in fluvial style would reflect late Transgressive System Tract to Highstand System Tract high accommodation conditions, and the relative Maximum Flooding Surface would lie within these deposits. Unit 3 is bounded at the top by an erosional unconformity that in well logs appears as a prominent leftward peak in the gamma ray response, indicating a significant increase in deposit grain size and consequently a significant depositional unconformity. Unit 3 thickness ranges from 120 to 80 meters.

Unit 4: Facies associations in Unit 4 are dominated by fining upward sequences of levee, crevasse splays, and overbank sheetflood deposits where small scale cross-beds, planar and undulatory laminated fine to very fine sand and silt, and thin organic lamination are the typical sedimentary structures. Frequently, "wet" and immature paleosols, interbedded amber-rich coal seams, and soft, light green to yellow volcanic ashes top overbank deposits. This stratigraphic architecture reflects a major shift in depositional style, suggesting medium to high accommodation and an overall trend toward aggradation. Radiometric ages from a bentonitic layer found at approximately 90 meters above the unit 3-4 boundary reveal an age of 73.25 ± 0.25 My (David Eberth, personal communication, 2006), roughly equivalent to the maximum transgression of the Bearpaw Sea in central and southern Alberta (*Baculites compressus* zone, 73.4 My: Obradovich, 1993). Thus, radiometric ages and variations in the fluvial depositional setting would confirm that the Bearpaw seaway regression in Alberta started earlier in the north western regions than elsewhere.

At the top of unit 4 is the Red Willow Coal Zone (Dawson et al., 1994) that includes the first appearance of thick (up to 1.5 m), laterally continuous coal seams within the Wapiti Formation. Palynological data indicate a late Campanian – earliest Maastrichtian age (Dawson et al., 1994) for the coal seams. The presence of a thick coaly interval is consistent with variation in the depositional trends observed in the transition from unit 1 and 2 of the Horseshoe Canyon Formation, interpreted as a direct reflection of the "Drumheller Marine Tongue" transgressive event at 70.5 My (Eberth, 2002; Eberth and Deino, 2005). The thickness of unit 4, including the Red Willow Coal Zone, is approximately 200 meters.

Unit 5: the uppermost section of the Wapiti Formation displays a depositional style similar to that of unit 4, with an alternation of fine paleochannel sandstones and overbank facies indicating a multi-storeyed small channel system. Sandstone units range from 10 to 100 cm, and are usually fining upward deposits capped by muddy/coaly horizons. Near the top of the unit, several thicker, continuous coal seams are developed and are currently referred to the Cutbank Coal Zone (Dawson et al., 1994). The lowermost coal seams are considered equivalent in age to the Thompson Coal Zone of the Alberta plains, and overlying deposits have been correlated with unit 5 of the Horseshoe Canyon Formation (Eberth, 2002) and possibly with the Whitemud and Battle formations. The top of the unit is bounded by a sharp erosional contact with the overlying massive, medium to coarse grained sandstones of the Entrance Member, that outcrops mostly along the Cutbank River. The thickness of Unit 5 is 160 meters. Importantly, the presence of the Cutbank Coal Zone is in contrast with the lacustrine facies of the Whitemud and Battle formations, indicating different climatic, environmental, and depositional conditions in the region.

The uninterrupted terrestrial record of the Wapiti Formation preserves a variety of depositional and environmental changes during the Campanian-Maastrichtian interval. Proposed units have been preliminarily correlated with age equivalent deposits of Alberta and Alaska (Figure 2). In particular, the high accommodation rate and aggradation trend observed in unit 3 deposits indicate the influence of the Bearpaw seaway on inland fluvial systems; the Red Willow Coal Zone within the fluvial deposits of unit 4 correlates with the "Drumheller marine tongue" transgressive event and probably reflects a major climatic change that involved north-western Alberta at the end of the Campanian.

Lastly, the Wapiti Formation produces a diverse terrestrial vertebrate fauna that to date includes several dinosaur groups (hadrosaurids, ceratopsids, ankylosaurs, tyrannosaurids, troodontids, droameosaurids) as well as crocodiles, exquisitely preserved squamates, turtles, mammals, and amphibians. Because the Wapiti Formation is 1) the sole uninterrupted terrestrial latest Cretaceous fossil-bearing unit in North America, and 2) between the mid-latitude southern Alberta and Montana and the high-latitude Alaska, further paleontological studies will reveal the nature of the transitional faunas between southern Alberta and Alaska and shed light into migratory, evolutionary, and biogeographic aspects of vertebrate distribution in North America at the end of the Cretaceous.

References:

Brinkman, D. 2003. A review of nonmarine turtles from the Late Cretaceous of Alberta. Canadian Journal of Earth Sciences, **40**: 557-571.

Dawson, F., Kalkreuth, W., and Sweet, A. 1994. Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta. Geological Survey of Canada Bulletin 466, 60 pp.

Eberth, D. 2002. Review and comparison of Belly River Group and Edmonton Group stratigraphy and stratigraphic architecture in the southern Alberta plains. CSPG Diamond Jubilee Convention, Program and Abstracts 117. Abstracts of Technical Talks, Poster & Core Displays including Extended Abstracts. PDF file 227S0125. Compact Disc.

Eberth, D., and Deino, A. 2005. New 40Ar/39Ar ages from three bentonites in the Bearpaw, Horseshoe Canyon and Scollard formations (Upper Cretaceous-Paleocene) of southern Alberta. *In* Dinosaur Park Symposium – Short Papers, Abstracts, and Program. Special Publication of the Royal Tyrrell Museum. *Edited by* D. Braman, F. Therrien, E. Koppelhus, and W. Taylor, pp 23-24.

Eberth, D. 2005. The Geology. *In* Dinosaur Provincial Park, a spectacular ecosystem revealed. *Edited by* P. Currie and E. Koppelhus. Indiana University Press, Bloomington, pp. 54-82.

Obradovich, J. 1993. A Cretaceous time-scale. *In* Evolution of the Western Interior Basin: Geological Association of Canada Special Paper 39. *Edited by* W. Caldwell and E. Kauffman, pp.379-396.

Phillips, R. 2003. Depositional environments and processes in Upper Cretaceous nonmarine and marine sediments, Ocean Point dinosaur locality, North Slope, Alaska. Cretaceous Research, **24**: 499-523.

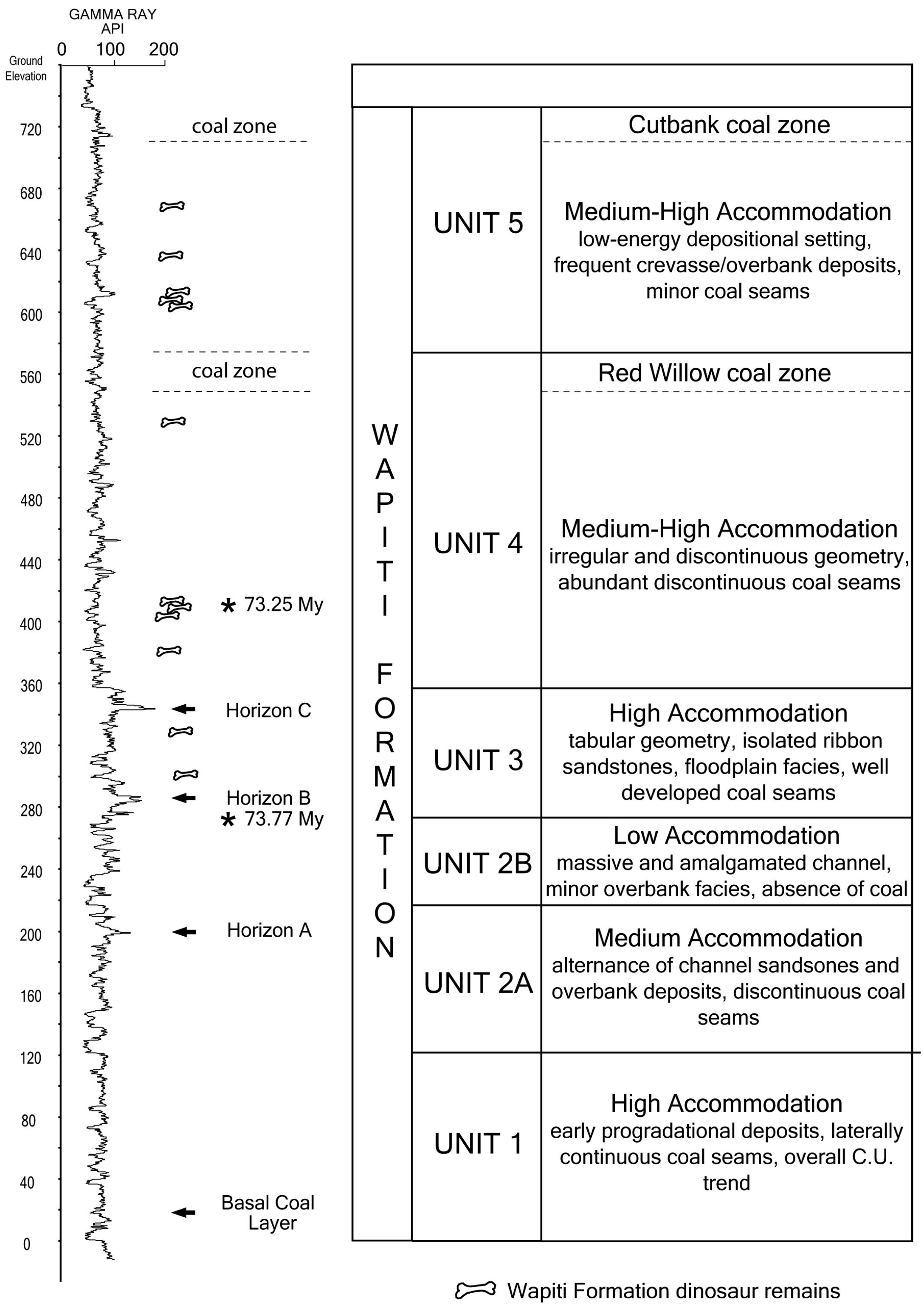
Tanke, D. 2004. Mosquitoes and mud – the 2003 Royal Tyrrell Museum of Paleontology expedition to the Grande Prairie region (north western Alberta, Canada). Alberta Paleontological Society Bulletin, **19**(2): 3-31.

Tanke, D. 2006. Sixty years of *Pachyrhinosaur* (Dinosauria: Ceratopsidae) discoveries in north America. Alberta Paleontological Society, Tenth Annual Symposium Abstract: 38-56

Figure Caption:

Fig. 1: Interpretation of Wapiti Formation reference log (gamma ray curve), well 7-27-068-11W6.

Fig. 2: stratigraphic chart showing the ages of Campanian-Maastrichtian deposits of Alberta and Alaska. After Phillips, 2003, Fiorillo, Pers. Comm. 2007, for Alaska; Eberth, 2005, Eberth and Deino, 2005, Braman, Pers. Comm. 2007, for central and southern Alberta; Brinkman, 2003 for southern plains of Alberta.



GAMMA RAY
API
0
100
200
Ground Elevation
720
680
640
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0
coal zone
coal zone
* 73.25 My
Horizon C
Horizon B
* 73.77 My
Horizon A
Basal Coal Layer
WAPITI FORMATION
UNIT 5
Cutbank coal zone
Medium-High Accommodation
low-energy depositional setting, frequent crevasse/overbank deposits, minor coal seams
UNIT 4
Red Willow coal zone
Medium-High Accommodation
irregular and discontinuous geometry, abundant discontinuous coal seams
UNIT 3
High Accommodation
tabular geometry, isolated ribbon sandstones, floodplain facies, well developed coal seams
UNIT 2B
Low Accommodation
massive and amalgamated channel, minor overbank facies, absence of coal
UNIT 2A
Medium Accommodation
alternance of channel sandsones and overbank deposits, discontinuous coal seams
UNIT 1
High Accommodation
early progradational deposits, laterally continuous coal seams, overall C.U. trend
Wapiti Formation dinosaur remains

Figure 1

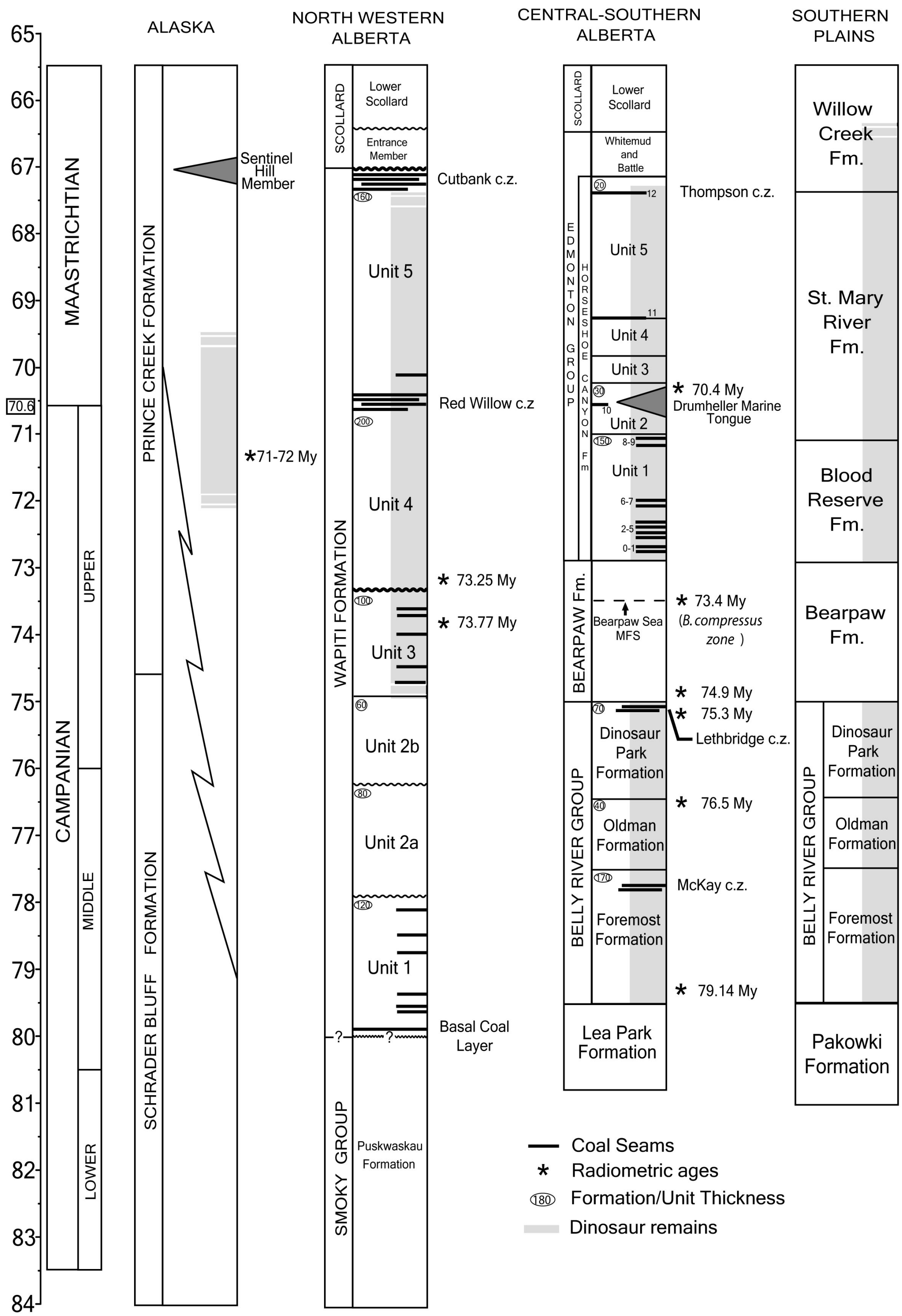

ALASKA
NORTH WESTERN ALBERTA
CENTRAL-SOUTHERN ALBERTA
SOUTHERN PLAINS
MAASTRICHTIAN
CAMPANIAN
UPPER
MIDDLE
LOWER
70.6
PRINCE CREEK FORMATION
SCHRADER BLUFF FORMATION
Sentinel Hill Member
*71-72 My
SCOLLARD
Lower Scollard
Entrance Member
Cutbank c.z.
Unit 5
Red Willow c.z
Unit 4
73.25 My
73.77 My
Unit 3
Unit 2b
Unit 2a
Unit 1
Basal Coal Layer
WAPITI FORMATION
SMOKY GROUP
Puskwaskau Formation
Whitemud and Battle
Thompson c.z.
EDMONTON GROUP
HORSESHOE CANYON Fm
Unit 4
Unit 3
Unit 2
Unit 1
70.4 My
Drumheller Marine Tongue
BEARPAW Fm.
Bearpaw Sea MFS
73.4 My
(B. compressus zone)
74.9 My
75.3 My
Lethbridge c.z.
BELLY RIVER GROUP
Dinosaur Park Formation
Oldman Formation
Foremost Formation
76.5 My
McKay c.z.
79.14 My
Lea Park Formation
Willow Creek Fm.
St. Mary River Fm.
Blood Reserve Fm.
Bearpaw Fm.
Pakowki Formation
Coal Seams
Radiometric ages
Formation/Unit Thickness
Dinosaur remains

Figure 2

33rd International Geological Congress – Oslo 2008

Sequence Stratigraphy of the Fluvial Wapiti Formation, Grande Prairie region, Alberta, Canada

Fanti, Federico* and Catuneanu, Octavian**

* Department of Earth and Geoenvironmental Sciences, University of Bologna, Via Zamboni 67, I-40127 Bologna, Italy. E-mail: federico.fanti@unibo.it

** Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences Building, Edmonton, Alberta, Canada. E-mail: octavian@ualberta.ca

The lower Campanian to upper Maastrichtian Wapiti Formation in north-western Alberta and north-eastern British Columbia is an undifferentiated lithostratigraphic unit that includes interbedded fluvial sandstone and siltstone with minor mudstone and coal, and subordinate lacustrine deposits. Fundamental questions about this succession include its subdivision into regionally mappable sequences, as well as the correlation of such sequences with the better known lithostratigraphic units in central and southern Alberta. This study reveals that the Wapiti Formation consists of four unconformity-bounded depositional sequences, which have been documented in outcrop and well logs; their study and description have been based on sequence stratigraphic methods, well-log signatures, facies analysis, and fossil associations. In ascending order, sequence 1 marks the transition from the underlying marine facies of the Puskwaskau Formation to the Wapiti fluvial facies, and consists of strongly progradational and aggradational (high accommodation) deposits. Sequences 2 and 3 consist of amalgamated channel-fill deposits at the base (low accommodation), which grade upwards into more floodplain-dominated successions (high accommodation). Preliminary results indicate that the maximum flooding surface of the Bearpaw seaway, which is a reference marine unit in central and southern Alberta, lies within the fine-grained fluvial deposits in the upper portion of sequence 3. Sequence 4 is dominated by channel sediments and extensive overbank facies, indicating high accommodation and an overall trend of vertical aggradation. Within sequence 4, the Red Willow Coal zone is age-equivalent to the Drumheller Marine Tongue transgressive event and marks another maximum flooding surface within the fluvial deposits of the Wapiti Formation.

Key words: Wapiti Formation, fluvial sequence stratigraphy, Upper Cretaceous, Alberta