Evolution of the Western Interior Seaway in west-central Alberta (late Campanian, Canada): Implications for hydrocarbon exploration

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Research paper

Evolution of the Western Interior Seaway in west-central Alberta (late Campanian, Canada): Implications for hydrocarbon exploration

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ABSTRACT

This study presents the first integrated, high-resolution stratigraphic analysis of a large area of the Cretaceous Western Interior Basin in Alberta (western Canada), providing new tools to discriminate sedimentary processes and stratigraphic patterns of transgressive-regressive (T-R) cycles in correlative marine and non-marine domains. We integrate gamma ray well-log analysis, measured sections, and paleontological data to determine sediment accumulation and distribution during the second-order T-R cycle of the late Campanian Western Interior Seaway over a previously unstudied area encompassing approximately 97,000 km^2 of the Alberta foreland basin. The Bearpaw Formation, historically regarded as the product of a single transgression, is shown to include two T-R cycles, whose timing is constrained by new chronostratigraphic data that provides an unprecedented resolution (~200 kyr) for the Cretaceous of western North America. Seven reference stratigraphic markers were mapped across the study area from the marine deposits into the fluvial domains. 3D-modelled stratigraphic surfaces and stratigraphic intervals resulted in isopach maps for consecutive systems tracts, allowing detailed interpretations of their architecture and patterns of sediment accumulation. Our analysis provides paleogeographic maps for the Western Interior Seaway, focusing primarily on the evidence of the paleo-coastlines during the documented cycles. The distribution of fine-grained, primarily marine, sediments resulted in an effective seal for hydrocarbon accumulation in the Belly River Group. Further oil migration upsection, within the Edmonton group, was pre-vented by the occurrence of these sealing units. Data support the interpretation that eustasy provided the main control on the evolution of the Western Interior Seaway during the late Campanian.

1. Introduction

The Bearpaw Formation is a late Campanian age marine unit deposited in the Western Interior Basin (WIB) of Canada and United States between 74 and 73 Myr (Rogers et al., 2016; Eberth and Kamo, 2020). Exposures of this Formation extend over much of northern and central Montana (U.S.A.) as well as in the southern part of Alberta and Saskatchewan (Canada). The lithostratigraphic interval represented by the Bearpaw Formation separates two major clastic wedges: in ascending order the Belly River and Edmonton groups, both renowned for their remarkable fossil record and studies on the evolution of clastic systems (Russel and Chamney, 1967; Dodson, 1971, 1990; Currie and Koppelhus, 2005; Larson, 2010; Larson et al., 2013; Eberth et al., 2013; Cullen and Evans, 2016; Gilbert, 2019). As the Bearpaw Formation has a complex lateral relationship with the correlative non-marine units of the Belly River and Edmonton groups, previous sequence stratigraphic studies investigated the possibility of defining mappable transgressive–regressive (T-R) sequences across Alberta, integrating exposures and geophysical well-log signatures. In the southern plains of Alberta, the Bearpaw Formation represents a second-order transgressive-regressive cycle, within which higher frequency (third-, fourth- and fifth-order) T-R sequences are nested (Hathway, 2016, and refer-ences therein). The time-transgressive geographic evolution of the Western Interior Seaway is reflected by the documented distribution of fine-grained, primarily marine, sediments that mark the Bearpaw For-mation. This likely also resulted in a primary control on hydrocarbon accumulation as the Bearpaw Formation separates the Belly River and Edmonton groups, two major non-marine, clastic systems dominated by fluvial deposition. Oil fields have been discovered and exploited in the Belly River Formation: fluvial channel fills have formed traps in the western portions of the Alberta Basin, whereas to the east accumulation follows updip sandstone pinchouts (Creaney et al., 1994). The Belly

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River Group has been the subject of multiple oil-related investigations as it may form regionally prospective trends within the Alberta Basin. This Group was considered and explored as a further target with respect to the deeper Cardium Formation (Plint et al., 1986; Putnam, 1993). The hydrocarbon fields exploited in the Belly River Group are now believed to be bordered by updip faults that seal major channel fills (Putnam, 1993) and no information is provided on the sealing efficiency of those faults nor on the occurrence of overlying sealing stratigraphic units. Despite such premises, our comprehension of Bearpaw Formation sedi-mentary dynamics, extension of sequence boundaries in correlative non-marine deposits, and ultimately reciprocal stratigraphies (related to patterns of base-level change across the foreland system) remains limited as two critical lines of investigation have been only marginally addressed.

First, Bearpaw Formation and correlative deposits along the margin of the Canadian Cordillera remain largely understudied, although they provide critical information to decipher the paleogeography and depositional setting of a large sector of the WIB during the late Campanian. This interval includes the non-marine, correlative deposits of the Bearpaw Formation that occur in the fluvial beds of the Wapiti Formation, a clastic wedge that extends over much of the northernmost section of the Alberta foreland basin (Fanti and Catuneanu 2009, 2010 and references therein). Although several lines of investigation support the occurrence of Bearpaw deposits in western Alberta (Jerzykiewicz, 1996; Fanti and Catuneanu, 2010; Koppelhus and Fanti, 2019) a combination of limited exposures, lack of systematic coring and ambiguous well-log signatures precluded high-resolution studies in this area. Prior to this study, this area of transition from marine to non-marine domains was largely un-known and unmapped (Jerzykiewicz, 1997; Chen et al., 2005; Fanti and Catuneanu, 2009, 2010).

Second, the mode and tempo of both eustasy and tectonics on the evolution of the foreland system remains unsolved and debated, as most of available data refer exclusively to marine deposits and lack precise or high-resolution chronostratigraphic control. As western Alberta pre-serves a record of interbedded marine and non-marine facies related to the Western Interior Seaway, it offers a unique insight into the large- scale architecture of T-R cycles, making the Bearpaw events a remark-able case study. Our study aims to provide new data to discriminate, with unprecedented resolution, the dynamics of the Bearpaw T-R cycles with a sharp focus on how major stratigraphic and sequence strati-graphic surfaces define discrete units in primarily non-marine settings. In so doing, we combine well-log analyses, high-resolution GIS-based 3D reconstructions, and selected exposures in order to provide a robust stratigraphic framework within which more localized observation could be placed and rationalized. Results provided in this study allow discriminating previously unmapped depositional domains in west- central Alberta and their relative shifts during the Bearpaw time. Consequently, data presented here provide definitive information regarding the way in which the Bearpaw T-R cycles control hydrocarbon migration and accumulation in the late Campanian age successions of west-central and southern Alberta.

2. Geological setting

2.1. Study area, stratigraphic, and structural setting

The main deformation events recorded in the Alberta foreland basin took place during two orogenic periods: from Late Jurassic to Early Cretaceous and from Late Cretaceous to Paleocene (Bally et al., 1966; Price and Mountjoy, 1970; Price, 1981; Chamberlain et al., 1989; Underschultz, 1991; Jerzykiewicz and Norris, 1994; Jerzykiewicz, 1997). Compressive deformation from Jurassic to Paleocene transported the sedimentary units eastward towards the Alberta foreland basin (McMecham et al., 1993) forming a fold-and-thrust belt that propagated in the Alberta Foothills (Dawson et al., 1990, 1994). The foreland Mesozoic and Cenozoic strata dip to the SSW, although in the foothills area they are folded on thrust anticlines and backthrusts (Stockmal et al., 2001), reversing their dip to the NNE and creating the western limb of the Alberta syncline (Pana and Van Der Pluijm, 2015). Shales of the Bearpaw Formation could have served as main detachment horizon of later thrust sheet formation in the foothills (Stockmal et al., 2001). The Western Interior Basin developed on the eastern side of the Cana-dian Rocky Mountains where successions from the Paleozoic to the Cenozoic ages, that overlie the crystalline basement, occur (Lee et al., 2018). This basin is dominated by western provenance siliciclastic successions produced by convergent tectonics along the western margin of the North American Craton (Monger, 1989).

Within this framework, our study area encompasses approximately 96.600 km^2 in west-central Alberta and extends N–S between the cities of Grande Prairie and Calgary and W-E between the deformation front of the Rocky Mountains and Edmonton (Fig. 1). The stratigraphic nomenclature and framework for the Upper Cretaceous strata in Alberta vary substantially with respect to the proximity to the foothills as well as from north to south. To the north and to the west of the city of Edmonton, the Wapiti Formation is time-equivalent to the Belly River Group (Foremost, Oldman, and Dinosaur Park formations), the Bearpaw Formation, and the Edmonton Group (Horseshoe Canyon and Battle formations) (Fig. 2). This clastic wedge is also correlative to the Brazeau Formation in the central foothills. The Wapiti Formation overlies the marine deposits of the Puskwaskau Formation, which is correlative with the Wapiabi Formation in the central foothills and the Lea Park For-mation in the southern plains (see Fanti and Catuneanu, 2009; Eberth and Braman, 2012 for a detailed nomenclatural review) (Fig. 2).

2.2. The Bearpaw Formation and correlative deposits in Alberta

Numerous publications have dealt with the Bearpaw Formation providing valuable stratigraphic, structural and paleontological data (Wall and Singh, 1975; Dawson et al., 1990, 1994; Ainsworth, 1994; Wood, 1994; Cant, 1995; Catuneanu et al., 1997, 2000, 2011; Leckie et al., 1997; Catuneanu, 2006; Hathway, 2016; Gilbert and Bamforth, 2017; Gilbert et al., 2019). The Bearpaw Formation accumulated in an epeiric sea, which transgressed over non-marine deposits. The Bearpaw Formation includes a vast array of depositional facies representative of paralic settings, with lithologies ranging from marine shales to siltstones and sandstones. In western and central Alberta, deposition took place in coastal-to inner-shelf environments, whereas to the east Bearpaw de-posits are representative of more offshore marine environments. The thickness of the Bearpaw Formation varies from the north, with a 'zero edge' placed near the city of Edmonton, to approximately 200 m to the south of Calgary and to $\sim$400 m in southern Saskatchewan (Dawson et al., 1994; Hathway, 2016; and references therein). A combination of a series of bentonite beds and very fossiliferous layers allowed for a refined ammonite-based (primarily inoceramids) biozonation of the Western Interior Basin. In ascending order, the Bearpaw Formation in Alberta encompasses the *Didymoceras cheyennense*, *Baculites compressus*, and *Baculites cuneatus* ammonite zones (Kauffman et al., 1993; Tsujita and Westermann, 1998; Walaszczyk et al., 2001) (Fig. 2).

The complex, diachronous interval that characterizes the Bearpaw Formation with respect to the underlying Dinosaur Park Formation (Belly River Group) and overlying Horseshoe Canyon Formation (Edmonton Group) has been described in the literature for more than a century (the first study: Hatcher and Stanton, 1903). This led to the identification of mappable and stratigraphically constrained clastic wedges dominated by coal deposits, each bounded by marine shale and shallow-marine sandstones. This architecture has been interpreted as a combination of multiple factors, primarily sea-level change, orogenic phases, subsidence, and climate (Catuneanu et al., 1997, 1999; Eberth and Braman, 2012; Hathway, 2016). The stratigraphic revision of the Horseshoe Canyon Formation (HCFm) by Eberth and Braman (2012) provided a comprehensive column of the Bearpaw Formation with respect to underlying, overlying, and correlative non-marine deposits in

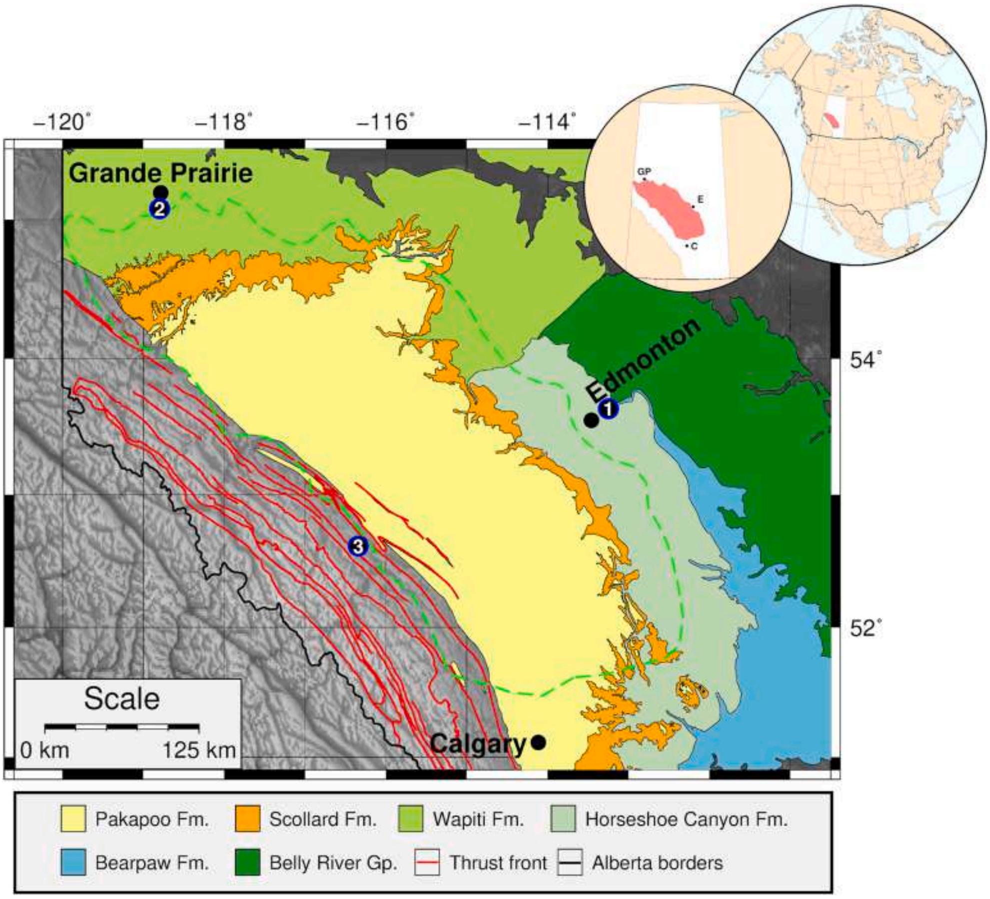

Fig. 1. Geological map of west-central Alberta with evidence of major external and foothills thrust fronts. Numbered circles indicate reference exposures for the studied interval (1 = Riverbend, 2 = Grande Prairie, 3 = Blackstone River; see Fig. 7). Green dashed line bounds the study area (located in the insets, red area). Background image and vector data: topography from ETOPO1 Global Relief Model (https://www.ngdc.noaa.gov) and vectors from the Alberta Geological Survey (modified after https://www.ags.aer.ca). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the province (Fig. 2). In ascending order, formally recognized units include Dinosaur Park Formation (top of the Belly River Group), lower Bearpaw tongue, Strathmore Member (the lower member within the HCFm), upper Bearpaw tongue, and Drumheller Member (HCFm). A third marine tongue introduced by Hamblin (2004) has been recognized by Eberth and Braman (2012) as the 'Dorothy Tongue', which occur to the south of our study area and is considered as correlative with the coaly deposits of the Drumheller Member. To the north and west, Wapiti Unit 3 is time equivalent to the maximum extension of the Western Interior Seaway based on sedimentological, radioisotopic, paleontolog-ical, and palynological data. Therefore, deposits that characterize Wapiti Unit 3 were interpreted to be correlative with the T-R cycles of the Bearpaw Formation (Fanti and Miyashita, 2009; Fanti and Catu-neanu, 2009, 2010; Larson et al., 2018; Koppelhus and Fanti, 2019; Sullivan et al., 2019).

Eberth and Kamo (2020) provided a comprehensive, calibrated chronostratigraphy for the Horseshoe Canyon and Bearpaw formations based on samples acquired in the Red Deer River valley of southern Alberta. New U–Pb CA–ID–TIMS ages confine the Bearpaw-Strathmore interval between 74.308 ± 0.031 and 73.1 ± 0.1 Myr. The Dorothy Bentonite (described in Lerbekmo 2002), which occurs near the base of the upper Bearpaw tongue, resulted in an interpolated age of 73.7 ± 0.1 Myr, further constraining the age of the Strathmore-upper Bearpaw tongue transition (Fig. 2).

3. Data and methods

3.1. Subsurface dataset

To develop a robust stratigraphic scheme, 977 gamma-ray well logs were included in our analyses and arranged in a grid of 31 cross-sections using IHS software Accumap and Acculog. The average distance between individual wells along the sections is ~10 km, although along reference sections it is often lower than 5 km. We included additional 141 reference wells located within main cross-sections to increase the resolution of our analyses (Fig. 3). Reference well logs available in the literature allowed for a more accurate discrimination of main stratigraphic surfaces. We included exposure-calibrated data available in the literature for the central plains of Alberta (Catuneanu et al., 1997; Eberth and Braman, 2012) as well as for the Grande Prairie and foothills regions (Jerzykiewicz, 1997; Fanti and Catuneanu, 2009, 2010) (Fig. 1). The sequence stratigraphic nomenclature and classification in this paper follow Catuneanu (2017, 2019a,b).

3.2. Criteria for well log correlations

As neither continuous nor large cores were available for the study area, the three-dimensional dataset presented here was created from the identification of major stratigraphic unconformities and marker beds. In ascending order, we identified the following stratigraphic markers: base of the Belly River Group (datum); base of the lower Bearpaw tongue on top of the Dinosaur Park Formation (and correlative deposits); maximum flooding surface (MFS) of the lower Bearpaw tongue; base of the Strathmore Member(Horseshoe Canyon Formation) on top of the lower Bearpaw tongue (and correlative deposits); base of the upper Bearpaw tongue on top of the Strathmore Member (and correlative deposits); MFS of the upper Bearpaw tongue; base of the Drumheller Member on top of the upper Bearpaw tongue (and correlative deposits).

A robust and unequivocal stratigraphic framework of non-marine successions based exclusively on geophysical data is commonly difficult to obtain given the limited lateral extent of fluvial depositional elements. As the Wapiti Formation deposits are primarily fluvial in origin,

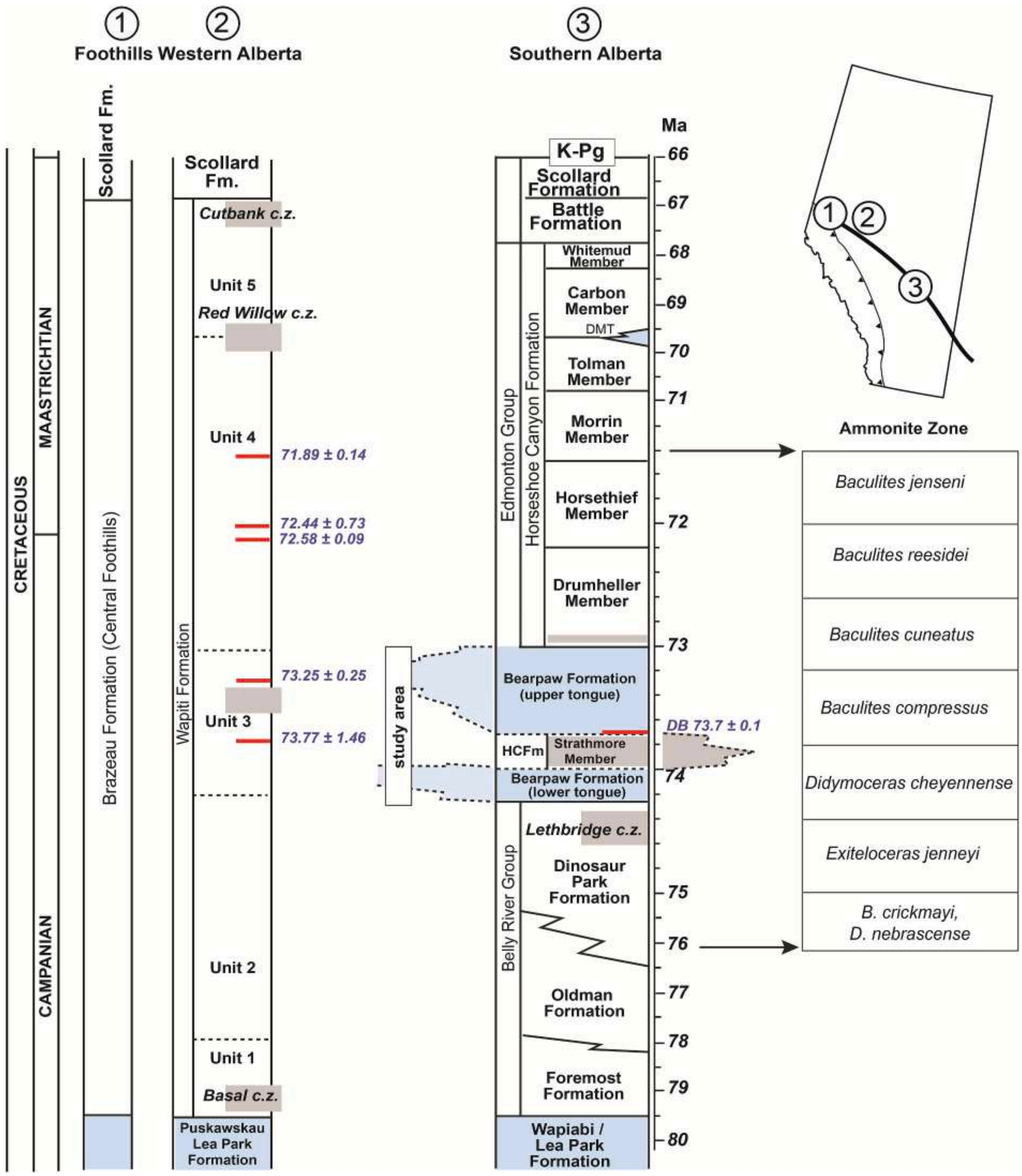

Fig. 2. Campanian to Paleogene lithostratigraphy and stratigraphic nomenclature for the study area (after Fanti and Catuneanu, 2009; Eberth and Braman, 2012), with indicated age constraints of the Bearpaw interval in southern Alberta. Red lines mark dated bentonites and grey squares indicate major coal zones (after Eberth, 2005; Currie et al., 2008; Fanti and Miyashita, 2009; Bell et al., 2014; Fanti et al., 2015; Eberth and Kamo, 2020). Marine reference formations in light blue. DB, Dorothy Bentonite. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

their correlative deposits discussed here are based on the identification of stratigraphic markers, corroborated by the occurrence and lateral mappability of coal seams/zones, bentonites, distinctive lithological contacts, and proximity to exposures. The area located to the south of Edmonton is object of substantial literature that provide solid con-straints for this study (Catuneanu et al., 1997; Jerzykiewicz, 1997; Eberth and Braman, 2012; Hathway, 2016). Following previous studies, beds exposed along the North Saskatchewan River valley north of Edmonton (WGS84: 53.675457, 113.294843) were examined for this study. The north-western limit of the study area is represented by the Grande Prairie region (Fig. 3), roughly in correspondence with the Wapiti River valley. Critical stratigraphic, paleontological, and chronostratigraphic data for this area have been made available in recent publications (Fanti, 2009; Fanti and Miyashita, 2009; Fanti and Catuneanu, 2009, 2010; Bell et al., 2013, 2014; Fanti et al., 2015; Bell and Currie, 2016; Larson et al., 2018; Koppelhus and Fanti, 2019; Sullivan et al., 2019). To the south, previous studies in the foothills of southern Alberta documented the occurrence of upper shoreface and coastal marsh sediments related to the transgressive-regressive phases of the Bearpaw Formation at approximately 71 Myr (Jerzykiewicz et al.,

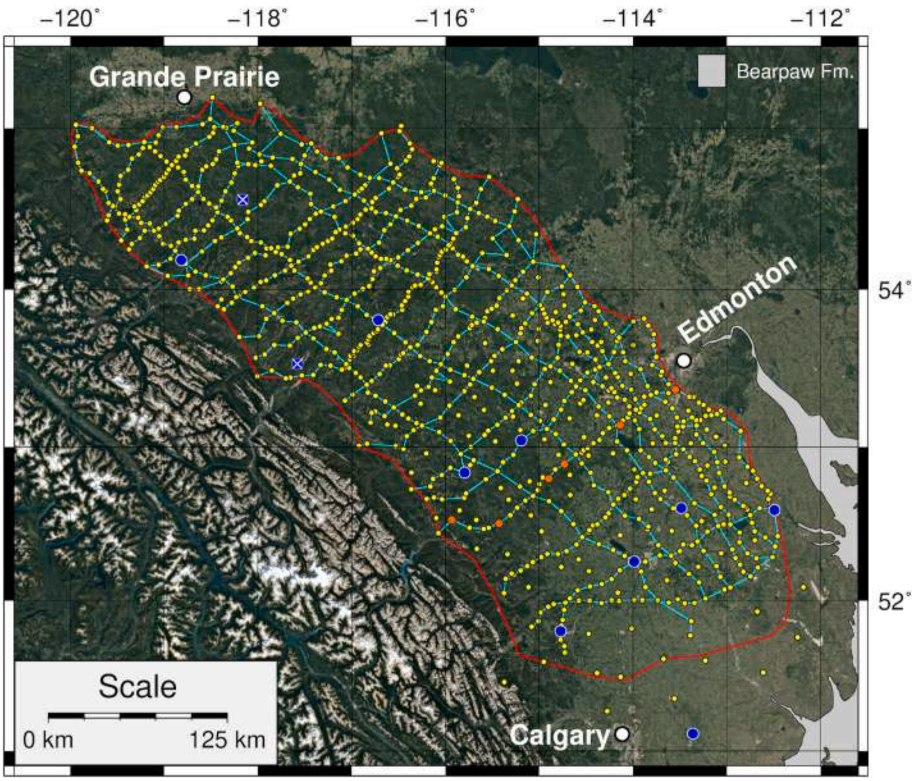

Fig. 3. Sections (light-blue) and well logs (yellow) used in this study, projected on a Google Earth satellite image. The area in grey represents the distribution of the Bearpaw Formation (see Fig. 1). Well logs indicated with blue dots have been used to compare depth correlations from this study and literature. Reference well logs are reported in Table 1 (crossed blue dots correspond to UWIs marked with an asterisk). Reference well logs shown in Fig. 4 are marked as orange dots. UWI = Unique Well Identifier. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1996). Correlative marginal marine sediments were reported farther north along the foothills in correspondence with major thrusts (i.e., Crowsnest Pass area, Tornado Mountain, Fording River, Blackstone River areas (see also Jerzykiewicz and Sweet 1986, 1988; Jerzykiewicz 1992, 1996, 2010; Dawson et al., 1994; Jerzykiewicz et al., 1996; Jerzykiewicz pers. comm. 2020).

Reference surfaces were marked on each well log to generate a dataset with georeferenced depths. The identification of each

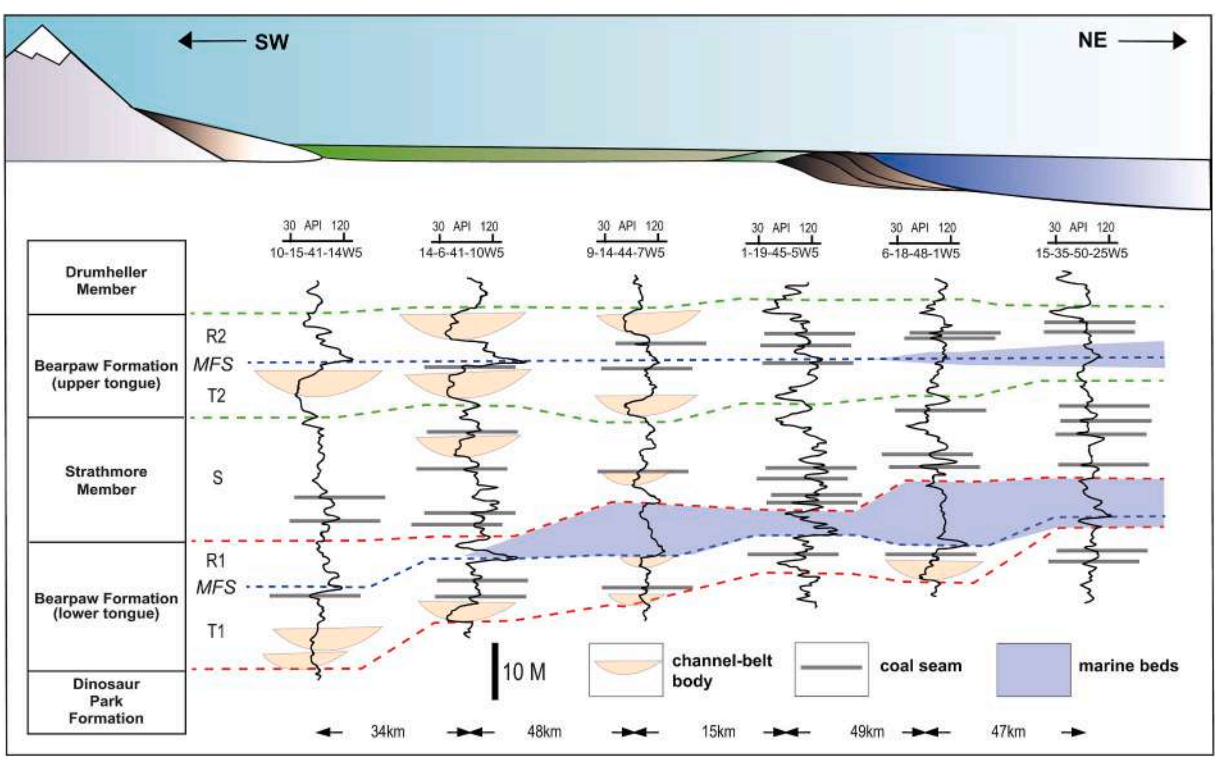

Fig. 4. Gamma-ray stratigraphic cross section illustrating the overall geometries, stacking patterns and stratigraphic surfaces (dashed lines) discussed in this paper. The stratigraphic *datum* is the Maximum Flooding Surface (MFS) of the Bearpaw Formation upper tongue. API = American Petroleum Institute units. See the reference map in Fig. 3 for the location of wells.

stratigraphic marker was the main tool used to infer non-marine sequence stratigraphic patterns related to the Bearpaw events in the study area. The stratigraphic relationships of such surfaces are shown in Figs. 4 and 5. For this study, the delineation of T-R sequences resulted the simplest approach to stratigraphic analysis. We used maximum flooding surface signatures within the Bearpaw Formation (lower and upper tongue) as primary reference surfaces. Although the identification of MFS signature across the study area allows for discussion of genetic stratigraphic sequences, this approach would limit observations to a fraction of the Bearpaw stratigraphic interval. Data collected for this study improved the resolution of observations by identifying the TS and RS surfaces for each cycle and the scheme of their expression is reported in Figs. 4 and 5. Consequently, for each tongue we discuss two juxta-posing systems tracts, transgressive (TST) and regressive (RST).

3.3. *Tridimensional processing*

Reference stratigraphic surfaces were identified and marked on each log using IHS softwares, exported and interpolated using GMT 5.4.5 (Generic Mapping Tools) scripts. The new dataset provided accurate Digital Elevation Models (DEM) with depths referred to modern sea level datum. Surfaces were reconstructed using a Green's function-based interpolation method (Wessel, 2009). We obtained a thickness map of six consecutive stratigraphic intervals with pixel-based subtractions of pairs of subsequent DEMs. 3D processing permitted to perform multiple analyses on acquired xyz coordinates, including cumulative thicknesses of selected stratigraphic intervals, variation in accumulation with respect to selected surfaces (isopachs) and volumetric measurements. This tridimensional reconstruction served as reference for the compar-ison with hydrocarbon fields distribution.

4. Results

4.1. *Thickness distribution from the base of the Belly River group to the base of the Bearpaw lower tongue TST*

The Puskwaskau-Wapiti contact (correlative of the Lea Park–Belly River contact) is used as datum. Fanti and Catuneanu (2009, 2010) discussed this transition from marine to continental deposits based on multiple exposures and well-log signatures in west-central Alberta. The stratigraphic interval delimited by the datum and the base of the Bearpaw lower tongue, proved to be crucial in testing the occurrence of anomalies in the depositional setting of the study area, such as those related to tectonic deformation. In the study area, subsurface units develop at a very low angle and conformably with respect to the datum plane. Three-dimensional reconstruction of stratigraphic surfaces and thickness variations in this interval supports an overall homogenous setting for the Belly River and correlative Wapiti deposits in the study area. This preliminary test was necessary to trace the subsequent stratigraphic surfaces and unit thicknesses in the selected stratigraphic intervals (Fig. 6). From the base of the Belly River Group to the base of the Bearpaw lower tongue (Fig. 6-A) it is possible to recognize three major areas of thickness distribution that develop parallel to the modern Rocky Mountains deformation front: > 400 m (4% of the area), 300–400 m (67% of the area), and <300 m (29% of the study area). Overall thick-ness decreases rapidly from the SW towards NE. We observe higher accumulation in the internal areas that correspond to major modern sediment inputs, suggesting that major sediment inputs were perpen-dicular to the raising cordillera (e.g. Putnam, 1993). This pattern sug-gests that sediment inputs and transport were primarily oriented along a SW-NE direction during the Campanian. By examining the map of the Belly River Group (Fig. 6A) it appears that the thickest succession is in the central area of the basin that corresponds to the main location of the oil fields named Peco and Pembina East (Putnam, 1993).

4.2. *Thickness distribution of the Bearpaw lower tongue TST (T1)*

This interval includes deposits stratigraphically bounded by the base of the Bearpaw lower tongue and its MFS. Isopach map of T1 highlights a heterogeneous distribution of sediment, with values ranging from 1 m to a maximum of 20 m. Values < 5 m cover 41% of the study area, whereas 52% is covered by 5–10 m thick deposits, and 6% by deposits thicker than 10 m. The latter are primarily localized in the northern part of the study area (Fig. 6-B) and are organized in elongated belts, oriented SW- NE. To the south, lower accumulation (<5 m) characterizes most of the study area, where patches of thicker sedimentary bodies (5–20 m) are randomly distributed. This area with lower accumulation covers the central area of the Belly River clastic system entrapping oil migration

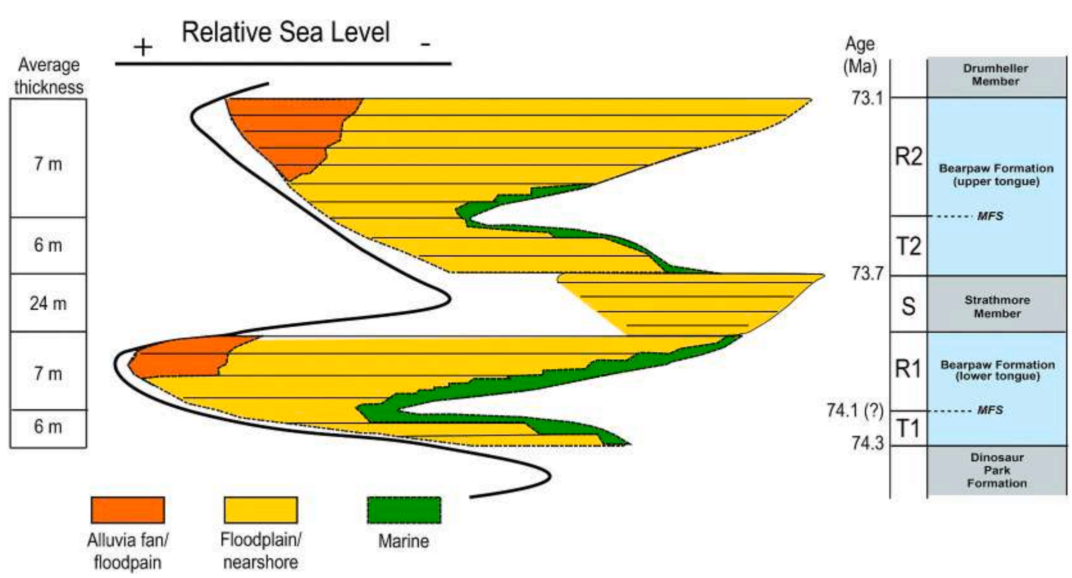

Fig. 5. Chronostratigraphic chart of the Bearpaw Formation stratigraphic interval. The TST and RST for the lower and upper Bearpaw tongues (and correlative deposits) are indicated as T1/R1 and T2/R2, respectively. Strathmore interval (S) is defined as accumulation between the top of R1 and the base of T2. Absolute dating and average thickness for each interval are indicated (Eberth and Kamo, 2020). The variation in lithologies, based on gamma ray logs, and the depositional architecture are interpreted as products of changes in relative sea level (see discussion in the text).

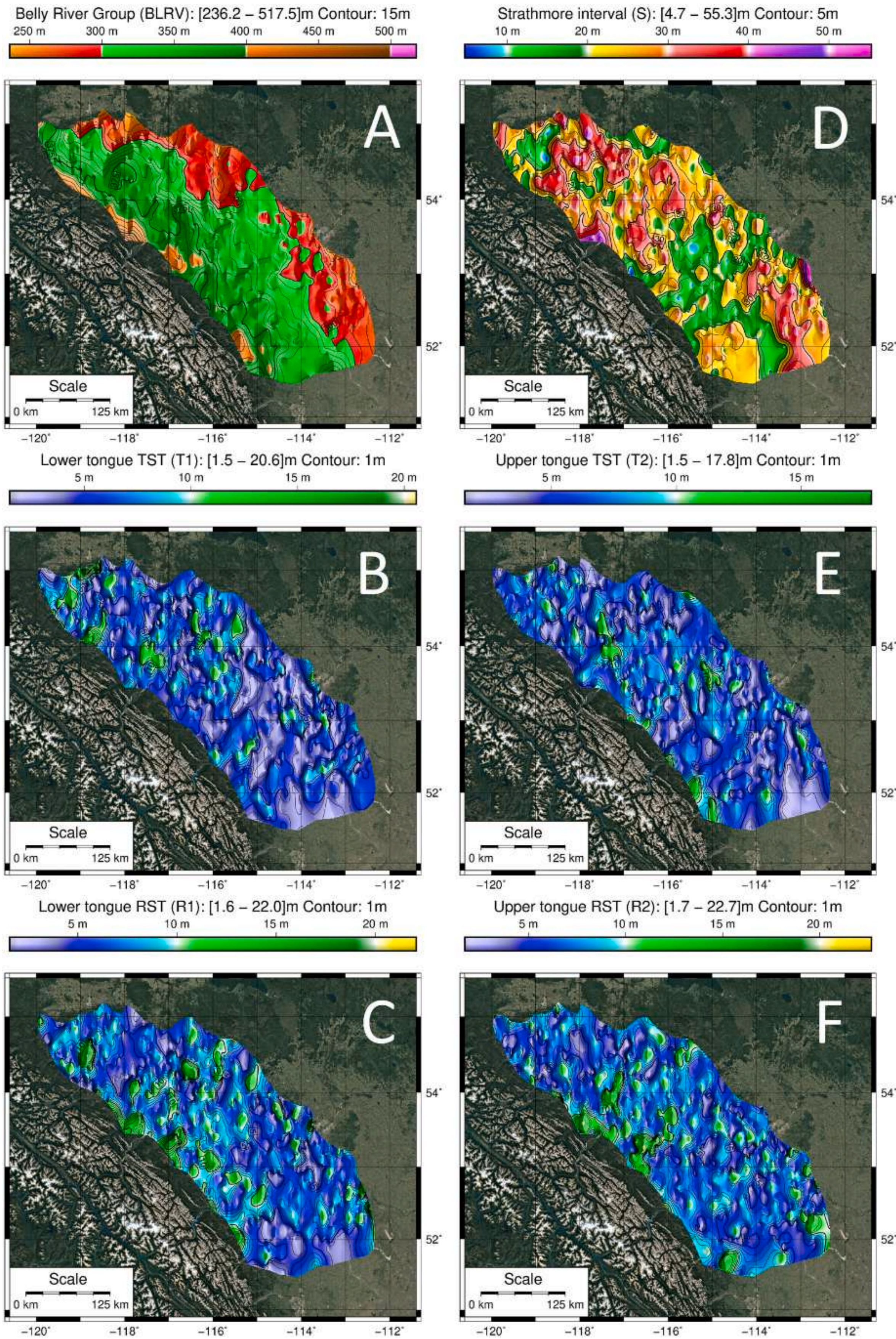

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Fig. 6. Thickness distribution maps for the six analyzed intervals represented with different color scales. Shaded relief illumination is doubled to emphasize the geometry of deposits, light comes from northeast and from southeast. Thickness ranges [min-max] are indicated. The color palette is reported above each map.The color palettes of the T1-R1 and T2-R2 maps are the same. A) Belly River Formation shows the inherited substratum for the subsequent accumulation depicted by the described intervals forming the Bearpaw succession. The base of the Belly River Group has been used as datum for the correlations. B) Thickness of the Bearpaw lower tongue TST (T1) is on average 6 m. C) Thickness of the Bearpaw lower tongue RST (R1) is on average 7 m. D) Thickness of the Strathmore interval (S) up to the base of the Bearpaw upper tongue is on average 24 m. E) Thickness of the Bearpaw upper tongue TST (T2) is on average 6 m. F) Thickness of the Bearpaw upper tongue RST (R2) is on average 7 m. (For interpretation of the references to color in this figure, the reader is referred to the Web version of this article.)

(Fig. 6-B). Estimated volume of sediment accumulated during this interval is 565 km^3, with an average thickness of 6 m (Fig. 5).

Geological samples representative of this interval were collected at Riverbend (North Saskatchewan River valley, north-east of Edmonton) and consist of dark grey shales rich in sponge spicules (Fig. 7-A). The MFS that bounds this interval has been locally used by previous authors to mark the Belly River (Dinosaur Provincial Park Formation) - Bearpaw transition, making it hard to document accumulation trends during the thin and geographically discontinuous TST of the lower Bearpaw tongue. Fanti and Catuneanu (2009, 2010) integrated subsurface, outcrop, and paleontological data to conclude that the non-marine de-posits of Wapiti Unit 3 are correlative with the Bearpaw Formation of central Alberta. Wapiti Unit 3 includes fine-grained floodplain deposits, bentonitic paleosols, lenticular organic-rich mudstones, coal seams, and peat horizons deposited by high-sinuosity aggrading channels (Fig. 7-B). The diverse vertebrate fauna collected from this interval is typical of wet lowland environments dominated by high water table, with taxa refer-able not only to terrestrial conditions but also to brackish and marine ecosystems (Fanti and Miyashita 2009; Koppelhus and Fanti 2019; Fanti pers. obs, 2020).

4.3. Thickness distribution of the Bearpaw RST lower tongue (R1)

The Strathmore Member – and its correlative deposits across the study area – has been defined as genetically confined by the MFSs of the lower and upper Bearpaw tongues (see also Eberth and Braman, 2012; Hathway, 2016). The high-resolution dataset presented in this study discriminates more detailed accumulation trends within the Strathmore Member. Three discrete phases characterize this interval: R1, prograd-ing S, and T2 (see description in paragraph 4.4 and 4.5). The lower part (R1) includes deposits that mark the transition from the marine Bearpaw shales to the sand and coal-dominated Strathmore beds (Fig. 6-C). The upper boundary of R1 is marked by the top of the coarsening up se-quences (Fig. 4). The R1 interval involves sediment volumes comparable with those documented for the T1 interval and thickness from 5 to 20 m. The 68% of the study area is covered by deposits within the range 5–10 m and 12% with a thickness higher than 10 m. Thicker deposits (>10 m) are primarily documented on the western border of the study area. They occur in correspondence with modern sediment inputs, with an overall fan-like plan geometry, extending mainly toward E-NE in the central study area. Estimated volume of sediment accumulated during this in-terval is 691 km^3 with an average thickness of 7 m (Fig. 5).

4.4. Thickness distribution of the Strathmore Member HCFm (S)

Much of the Strathmore Member accumulated between the end of the R1 and the base of T2 of the Bearpaw upper tongue. Isopachs of this stratigraphic interval record the maximum values, exceeding 50 m with an average value of 24 m (Fig. 5). Thicknesses under 20 m cover 29% of the study area, thicknesses between 20 and 30 m cover 49%, and over 30 m cover 22% of the study area. Although most of the thicker deposits (>40 m) are located close to the modern sediment inputs alluvial fans they appear also in the eastern margin of the study area, approximately 60 km to the SE of Edmonton. Isopachs between 20 and 40 m dominate the northwestern part of the study area (Fig. 6-D). Estimated volume of sediment accumulated during this interval is 2365 km^3, with an increase of 88% with respect to the T1+R1 interval (entire Bearpaw lower tongue).

4.5. Thickness distribution of the Bearpaw upper tongue TST (T2)

The T2 interval includes deposits from the base of the upper tongue up to its MFS and encompasses sediment volumes similar to the T1 in-terval. However, the spatial distribution of the deposits changed compared to T1 (Fig. 6-E). Areas with less than 5 m of sediment accu-mulation cover 34% of the study area, 61% is covered by 5–10 m, and the 5% by deposits thicker than 10 m. The average sediment thickness for this interval is 6 m (Fig. 5). Deposits with less than 5 m in thickness develop roughly SW-NE and extend over larger areas in comparison with T1. Thicker deposits (>10 m) are localized on the western border of the study area and accumulated in the central and southern areas, rather than in northern ones. Lower sediment accumulation (<5 m) is docu-mented in the more external south-eastern sectors of the study area, indicating a remarkable decrease in sediment supply when compared with the preceding S interval (Fig. 6-D). Estimated total volume of sediment accumulated during this interval is 579 km^3, a value only 2% higher than T1.

4.6. Thickness distribution of the Bearpaw RST upper tongue (R2)

The R2 interval records sediment accumulation deposited between the Bearpaw upper tongue MFS and the base of the Drumheller Member (and correlative strata). A comparison with the underlying interval does not document a substantial increase in sediment accumulation. Thick-ness values less than 5 m characterize about the 16% of the study area, 5–10 m represent 72%, and higher values (>10 m) characterize 12%. The area covered with less than 5 m thick deposits is reduced and restricted to narrow patches mainly aligned along a SW-NE direction. During the R2 interval, thick deposits (>10 m) accumulated primarily in the north-central part of the study area. Estimated volume of sediments accumulated during this interval is 700 km^3, a value only 1% higher than R1.

4.7. Rates of sedimentation

The stratigraphic interval discussed in this study is representative of approximately 1.2 ± 0.2 Myr, based on recent radioisotopic calibrations presented in Eberth and Kamo (2020). These chronostratigraphic con-straints are used here to infer rates of sediment accumulation (RSA) for discrete stratigraphic intervals. The average cumulative not-decompacted thickness of the intervals from T1 to R2 is 51 ± 8 m. As this interval encompasses approximately 1.2 Myr, the averaged RSA is 4.2 ± 0.7 cm/kyr.

Eberth and Kamo (2020) provided the most recent estimations of RSA for the Late Cretaceous of Alberta. Such values are claimed by the authors to be consistent throughout the Dinosaur Park, Bearpaw, and lower Horseshoe Canyon formations; the provided RSA for this entire interval is 8.1 cm/kyr (196 m/2.425 Myr). Eberth and Kamo (2020) pointed out that 8.1 cm/kyr is a relatively high rate compared to southern Alberta Upper Cretaceous non-marine sections (cf. 3.5–4.8 cm/kyr reported by (Eberth, 2005), and Lerbekmo et al., 2005). RSA documented in our study area are not comparable to those estimated by Eberth and Kamo (2020), or with those presented in Eberth (2005) and Lerbekmo et al. (2005) for the uppermost Belly River Group. Although the discrepancies in RSA values likely relate to different geographic areas, to the extension of Bearpaw marine tongues (i.e. southern vs central and western Alberta), and to a combination of multiple

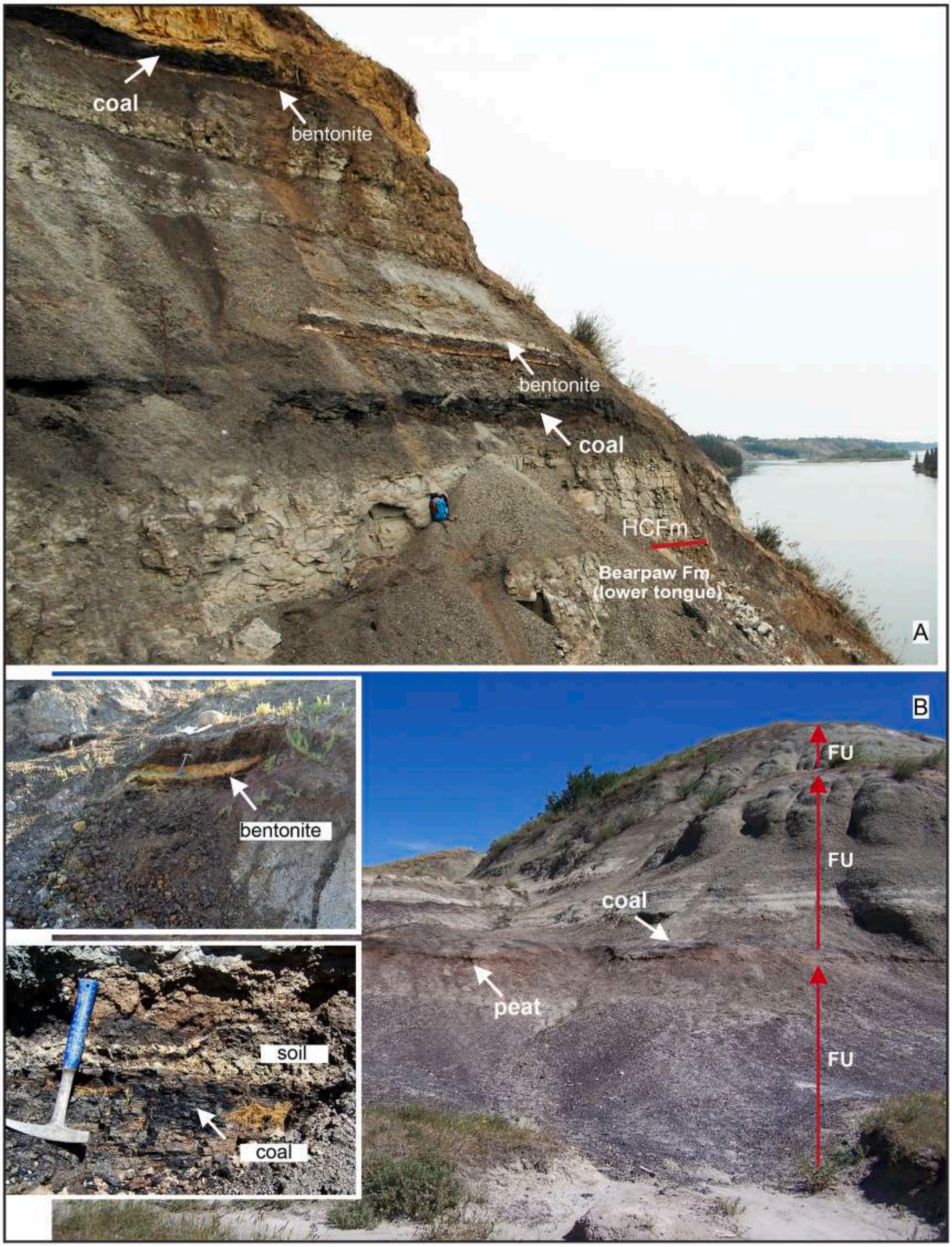


Fig. 7. A) Bearpaw Formation (BPFm) shale overlain by Horseshoe Canyon Formation (HCFm) basal sand-stones near Riverbend (Edmonton). Base contact of the HCFm is marked by the red line, followed by 2.2 m thick grey sandstones. Upsection coal seams and bentonitic paleosols are indicated. In the lower part of the outcrop, the contact between Belly River Group fine sands and BPFm was found 6 m under the HCFm – BPFm contact. B) Non-marine deposits of the Wapiti Formation Unit 3 near Grande Prairie, Alberta. Fine-grained, silt-dominated channel deposits are interbedded with mudstones, tabular peat, coal seams, and bentonitic paleosols (see text for descriptions). FU, fining upward. (For interpretation of the references to color in this figure, the reader is referred to the Web version of this article.)

depositional settings (i.e., marine, paralic, fluvial, coal zones, etc.), the dataset presented in this study refines the RSA estimates for more discrete depositional intervals. The upper tongue of the Bearpaw Formation accumulated between 73.7 and 73.1 Myr (Eberth and Kamo, 2020) and in our study area includes on average 13 m of deposits. Therefore, the RSA for the upper Bearpaw Formation tongue would be close to 2 cm/kyr. Radioisotopic ages indicate that the transgressive part of the lower Bearpaw Formation tongue accumulated between 74.3 and 74.1 Myr, with an average accumulation of 6 m, indicating a RSA value of 3 cm/kyr. The deposition of the prograding component of the Strathmore Member (R1+S) encompasses approximately 400 Ka (between 74.1 and 73.7 Myr), with an average accumulation of 32 m. The

RSA value for this interval is therefore close to 8 cm/kyr, although 80% of deposits accumulated during the progradation of the Strathmore lobes. RSA values for the Bearpaw Formation are therefore comparable with those estimated for southern Alberta (Eberth, 2005; Lerbekmo et al., 2005), although they change substantially when referred to spe-cific transgressive or regressive phases.

5. Discussion

5.1. Cumulative maps and sediment distribution

Isopach and cumulative thickness maps of sediment accumulation (Figs. 6 and 8 respectively) derived from the 3D database allowed documenting the spatial distribution through time of sedimentary bodies during the Bearpaw T-R cycles. Changes in sediment accumulation are likely products of changes in relative sea level and the development of TST and RST systems tracts (Fig. 5).

T1. The distribution of sediments of the TST of the lower Bearpaw tongue shows a uniform deposition draping the uppermost Belly River Group and equivalent deposits (Fig. 8-A and B). Overall geometries show minor differences from the underlying unit arranged as large lobe/fan-like bodies measuring up to 100 km in width with more accumulation occurring in the northern sectors of the study area. The most distinctive alluvial fan systems are located along the present-day Smoky River. Thickness maps revealed multiple areas of major sediment accumulation in the foothills region near the present-day deformation front. From south to north, these areas are roughly located along the Tay and Panther rivers, North Saskatchewan River and Athabasca River. We identify two areas characterized by low accumulation in the eastern and northwestern margin of the study area. The basal deposits of the lower Bearpaw tongue are extensively documented for southern Alberta, Sas-katchewan, and Montana where they are consistently characterized by a sharp and distinctive well-log signature, the juxtaposing of marine mudstone directly on top of coal-dominated beds, and a rapid transition into stacked coarsening upward marine, mud-dominated sequences (Catuneanu et al., 1997; Glombick, 2010; Rogers et al., 2016; Hathway, 2016; Street et al., 2019). Although this transition records a rapid change in the depositional settings (T1 represents approximately 200 kyr), no evidence of relevant disconformities has been reported in the literature nor observed in the study area, with the exception of a discontinuous ravinement surface (Catuneanu et al., 1997). In southern Alberta, the upper Dinosaur Park Formation records the transgression of the Bearpaw Formation and is dominated by tidally-influenced estuarine valley-fills associated with higher frequency changes in relative sea level (Eberth, 2002). The top of the Dinosaur Park Formation is represented by the Lethbridge coal zone, which developed as a result of rising water-table levels associated with the early transgressive phases of the Western Interior Seaway, and is characterized by laterally continuous coal seams. In southern Alberta and near the city of Edmonton, the basal contact of the lower Bearpaw tongue (Catuneanu et al., 1997; Glombick, 2010; Hathway, 2016; and references therein) is overlain by coarsening-upward intervals of silty mudstone with minor siltstone and sandstone (Eberth, 2005; Chen et al., 2005; Eberth and Braman, 2012; Hathway, 2016). This study indicates that during the TST of the lower Bearpaw tongue, west-central Alberta experienced higher sediment supply and accumulation compared to the historic study areas to the south.

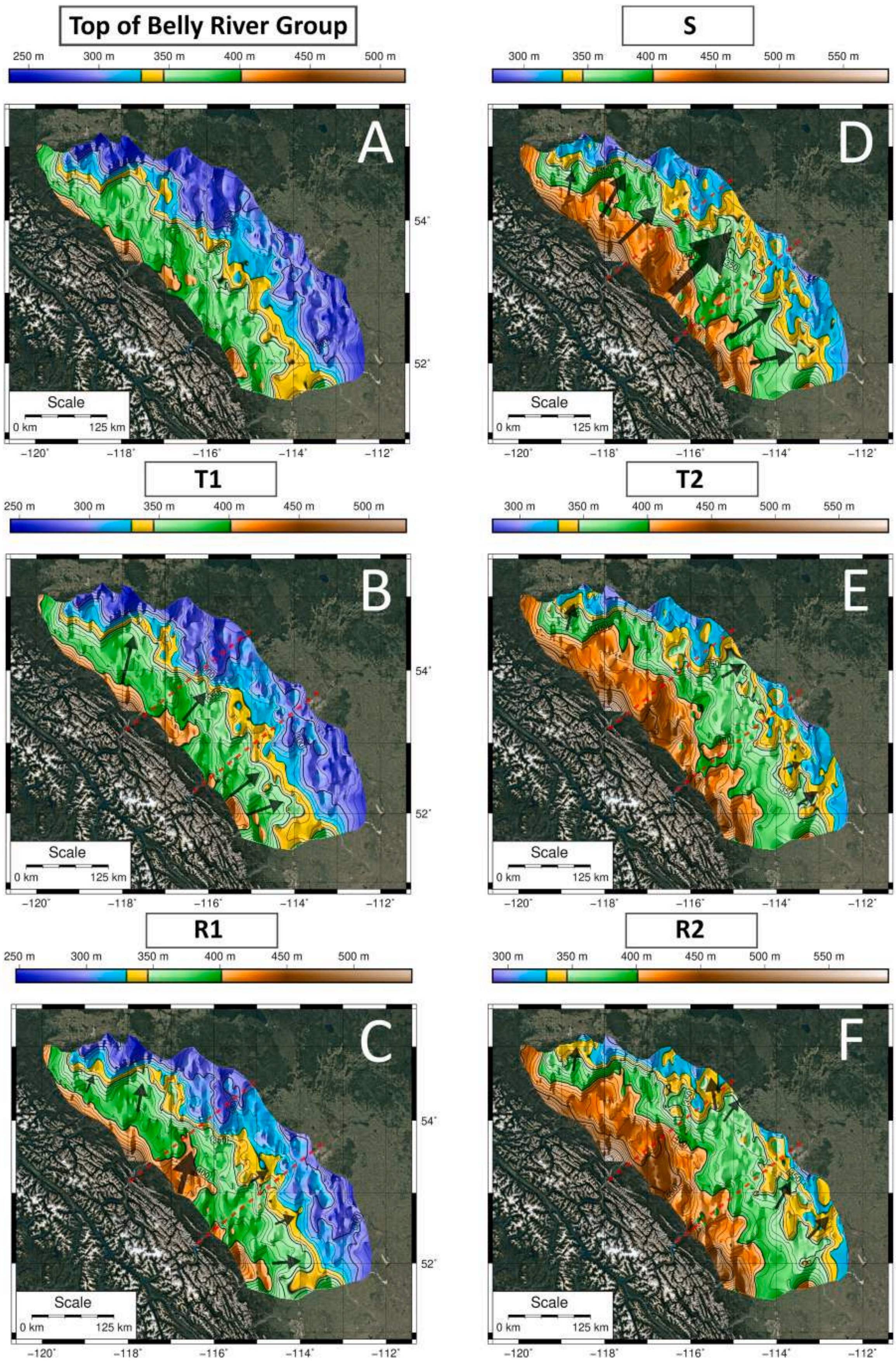
R1. This interval represents the regressive stage (RST) of the Bearpaw lower tongue and correlative non-marine beds of the Strathmore Member of the Horseshoe Canyon Formation. Data support a more pronounced partitioning of the study area into northern, central and southern sectors. Cumulative map (Fig. 8-C) indicates overall accumulation trends, with a basinward shift of depositional systems located in the central foothills, primarily between the Brazeau and Athabasca rivers. In the north, low accumulation persists in the distal part with minor progradation. The central area marks high sedimentation in the foothills that gradually decreases distally. In the southern sector we observed a progradation of the foothills system and a vast area of low accumulation located to the south of Edmonton, which is consistent with the occurrence of fine-grained, muddy sediments. At the time of writing, this interval has not been documented in outcrop. Eberth and Braman (2012) indicate that the lower deposits of the Strathmore Member in southern Alberta include mainly coal and non-marine carbonaceous shales, based on well-log signatures.

S. The isopach maps show a progradation of all depositional systems toward NE. In the foothills, high-accumulation areas extend up to a third of the study area and particularly along the Smoky, Athabasca, and Brazeau rivers and south of the North Saskatchewan River (Fig. 8-D). In the northern section, despite an overall progradational trend, an area of low-depositional rates persists east of the town of Grande Prairie. Major shifts in sediment accumulation are mapped in the central part of the area. The southern sector is less influenced by the overall prograding trend, including accumulation in the foothills area.

In the Edmonton area, the stratigraphic interval encompassing the lower Bearpaw tongue, Strathmore Member, and upper Bearpaw tongue has a thickness of approximately 50 m (Chen et al., 2005; Eberth and Braman, 2012; Hathway, 2016) and is dominated by alternating marine shales and coal-rich, paralic deposits. Published data about the deposi-tional geometries of the Strathmore Member suggest progradation to-ward the south, where large (>130 km in diameter) lobes with an eastward pinch-out have been documented (Eberth and Braman, 2012). The position of the maximum regressive shoreline of the Strathmore Member identified from our dataset is consistent with data presented by Eberth and Braman (2012) for the Red Deer area, with a NW-SE orien-tation. Cross-sections available for the southern part of the study area support aggradation during the deposition of the Strathmore Member, although little has been discussed about its genetic interpretation. Based on our dataset, we conclude that this discrete interval corresponds to the highest accumulation rates of the Strathmore Member.

T2. This interval deposited during the transgressive component of the Bearpaw upper tongue. Isopachs indicate minor variation in sediment distribution across the study area, except for the central sector where a shift toward NE is apparent in both proximal and distal sections (Fig. 8-E). The northern sector still displays persistent areas of low sediment accumulation. Similiar to the lower Bearpaw tongue, the onset of the second marine ingression in the study area is not represented by a sharp shift in lithologies and depositional settings. Basal sequences of this interval include a diverse array of deposits, including organic-rich mudstones, coal seams, and isolated channel bodies. The T2 interval differs from T1 in lacking a clear marine component, rather representing a widespread increase in the water table resulting in finer deposits and extensive coal zones. Such conditions persisted through the deposition of the Strathmore Member, although sediment accumulation increased remarkably during the S interval (see above). The lower Bearpaw tongue is characterized by tabular strata, whereas the upper tongue includes large clinoform geometries (Eberth and Braman, 2012; Hathway, 2016; this study). New paleogeographic and paleoecological reconstructions for the Campanian in Alberta provide new insights to understand the major faunal turnover in Alberta (Ryan and Evans, 2005; Mallon et al., 2012; Eberth et al., 2013).

R2. This interval records the final regressive stages of the Bearpaw Formation in the study area. Sedimentary input from the foothills became homogeneous, also documenting the final stage of the Bearpaw regression in the southern sector (Fig. 8-F). Areas of low accumulation persist near Grande Prairie and southeast of Edmonton, suggesting major sediment transport from the orogen without further supply from the foreland area. In central Alberta, the upper Bearpaw tongue T-R cycle encompasses approximately 600 kyr (Eberth and Kamo, 2020). Pending further chronostratigraphic controls on the Strathmore Member, data presented in Eberth and Kamo (2020) indicate that the upper tongue represents at least half of the entire time of deposition of the Bearpaw Formation and roughly twice the time of the lower tongue.



(caption on next page)

Fig. 8. Cumulative thickness maps of the Bearpaw succession highlighting the progressive variation of accumulation in the study area. Shaded relief illumination is doubled to emphasize the geometry of deposits, light comes from northeast and from southeast. Color palette shows same thickness intervals in each map. Black arrows indicate the relative magnitude and inferred shift of sediment accumulation. Red dashed lines bound the northwestern, central, and southwestern areas discussed in the text. A) Cumulative thickness map of the Belly River interval whose base is used as datum. B) Cumulative thickness map from the datum to the lower Bearpaw tongue MFS; higher accumulation areas are arranged as lobes. Low accumulation is recorded in the eastern margin of the area. C) Cumulative thickness map from the datum to the top of R1, showing a moderate basinward shift of the accumulation, manly developing in the central sector. D) Cumulative thickness map from the datum to the top of the Strathmore interval. Northeastward progradation is strongly pronounced in the central sector. E) Cumulative thickness map from the datum to the upper tongue MFS. Minor accumulation leads to quite null geometric variations in sediment stacking pattern. F) Cumulative thickness map from the datum to the final regression (R2). Filling up of the southern sector is achieved, whereas low accumulation persists to the north. (For interpretation of the references to color in this figure, the reader is referred to the Web version of this article.)

5.2. Paleogeography of the Bearpaw Formation

The new dataset presented in this study, combined with detailed analyses of sediment distribution offers the opportunity to infer the paleogeographic evolution of the Alberta Basin during the Bearpaw time (Fig. 9). We recognize three adjoining areas characterized by distinctive trends. Near the foothills, the proximal (western) area deposits consist of coarse, lenticular or laterally interfingering and amalgamated bodies. Such beds represent multiple stacked and laterally amalgamated fluvial channel sandstones and lack coal horizons (Jerzykiewicz and McLean, 1980; Jerzykiewicz, 1992; Fanti, 2009; Fanti and Miyashita, 2009; Fanti and Catuneanu, 2009; Sullivan et al., 2019; Jerzykiewicz, pers. Comm. 2020).

To the east, in the central area, the depositional architecture of channel bodies displays less laterally-amalgamated sandstone bodies, with an increase in single, fining-upward bodies interbedded with finer floodplain deposits. Discontinuous coal seams, interbedded with organic-rich mudstone (crevasse-splay, overbank) suggest accumulation within alluvial plains with high-water table conditions (Fig. 9-A and B). Such alluvial deposits, encompassing the larger part of the study area, are distally delimited by a narrow area characterized by stacked and high-frequency coarsening upwards trends during regressive phases. Tabular and laterally continuous sand bodies, possibly linked to littoral sandbars, can be mapped in this area. Cross-sections indicate extensive coal zones interfingering with claystone and siltstone deposits, as documented in the southern plains for the Strathmore Member deposits. The gamma ray signatures in this area are consistent with transitional deposits typical of coastal environments such as backswamps, estuaries, and barrier-lagoons. As this interval is critical to our understanding of the geographic extent of the Bearpaw Formation during its two T-R cycles, 28 wells were combined to document the vertical characteriza-tion of deposits, and the along-dip variation in lithologies and deposi-tional architecture (Fig. 9 and Table 1). Eastward of these wells, in the eastern distal area, the MFS expression on gamma ray logs is more consistent (even between distant logs), possibly due to the homogeni-zation related to the increase in marine influence. Sediment distribution patterns suggest complex environmental transitions, strongly evocative of tidal embayment with vast submerged areas. We recognize a distal area with distinctive upward-coarsening then fining sequences (CU-FU), clear MFS signature and homogeneous finer sediments that likely per-tained to a fully marine setting.

The paleogeographic maps presented in Fig. 9 allow the recon-struction of the geographic extent of the Bearpaw T-R events (Bustin and Smith, 1993; Dawson et al., 1990, 1994; Cobban et al., 1994; Roberts and Kirschbaum, 1995; Jerzykiewicz, 1997; Eberth and Braman, 2012; Slattery et al., 2015; Hathway, 2016; Blakey and Ranney, 2017) and highlight how they differ in terms of depositional environments in Alberta. The marine part of the lower Bearpaw tongue is widely distributed in the study area and its western boundary runs almost parallel to the deformation front. Coastal zones are narrowly elongated from the NW to the SE. On the contrary, marine deposits of the upper Bearpaw tongue are confined to most distal sectors of the study area. This paleogeography is inherited from the maximum extent of the pro-grading Strathmore Member and displays a complex geographic distri-bution of coastal-transitional environments. Possible shallow-marine conditions persisted to the north-west of Edmonton during this interval. Although previous paleogeographic maps for this stratigraphic interval depicted our study area either as emerged or with a shoreline confined to the south of Edmonton (Dawson et al., 1990, 1994; Roberts and Kirschbaum, 1995; Eberth and Braman, 2012; Hathway, 2016), our analysis is consistent with the previous interpretation of Fanti and Catuneanu (2009, 2010) and further refine the correlation of the Wapiti Formation with the Bearpaw cycles. Thus, a combination of geological and paleontological data support that marine conditions related to the Bearpaw Seaway in the latest Campanian persisted not only in southern Alberta but also to the north-west, in the Grande Prairie region and possibly toward British Columbia. This interpretation is supported by data introduced in this study, which revise previous hypotheses on the geographic extension of the Western Interior Seaway (Dawson et al., 1990, 1994; Jerzykiewicz, 1997; Catuneanu et al., 1997; Hamblin, 2004; Hathway, 2016).

5.3. Inferences on hydrocarbon prospectivity

The base of the Belly River Group at approximately 80 Myr (Eberth and Deino, 1992; Eberth, 2005; Rogers et al., 2016; Freedman Fowler and Horner, 2015) marks the onset of continuous continental deposition in the Alberta foreland basin from the Campanian onward, with the Bearpaw Formation representing the sole and final exception of marine depositional systems. Data presented here provide reliable tools to discriminate the Bearpaw events and investigate the nature of consec-utive T-R cycles in both marine and non-marine realms. The lower Bearpaw tongue is here interpreted as a rapid (almost 300 kyr long) marine ingression dominated by tabular geometries that originated in the shallow, epeiric Western Interior seaway. The transgression resulted in the widespread deposition of fine-grained sediments in marine to tidally-influenced coastal environments. The paleogeographic distribu-tion of the lower Bearpaw tongue (Fig. 9) and its trends in gamma ray curves clearly indicate a rapid drowning of the channel-delta system of the uppermost Belly River units (i.e. Dinosaur Park Formation and lateral equivalents). This is particularly evident in the most oil-productive area corresponding to the Peco and Pembina East fields (Fig. 10A). Such geometries support the interpretation that deposits accumulated during the T1 interval of the Bearpaw Formation acted as effective seal of those fields (Fig. 10B). In post-Bearpaw units, almost exclusively coalbed methane and water have been found in drilled wells. This indicates that the Cardium oils that sourced the Belly River sands have been prevented to migrate upsection in the permeable Horseshoe Canyon units (including the Strathmore Member).

Continental conditions (i.e. fluvial and coastal marsh sediments) characterize the overlying Strathmore Member (S) that represents less than 400 kyr and includes about 50% of all deposits accumulated during the Bearpaw time (the value refers to our S interval, and rises to 75% if we consider the Strathmore Member as the interval delimited by the MFSs of the lower and upper Bearpaw tongues). A second rise of the base level resulted in the deposition of clinothems forming the upper Bear-paw tongue. Previous studies interpreted such changes in depositional style as the result of changes in flexural subsidence rate and continuous sedimentation across the basin within the range of variations of the rates of base-level rise (Catuneanu et al., 1997, 1999; Fanti and Catuneanu,

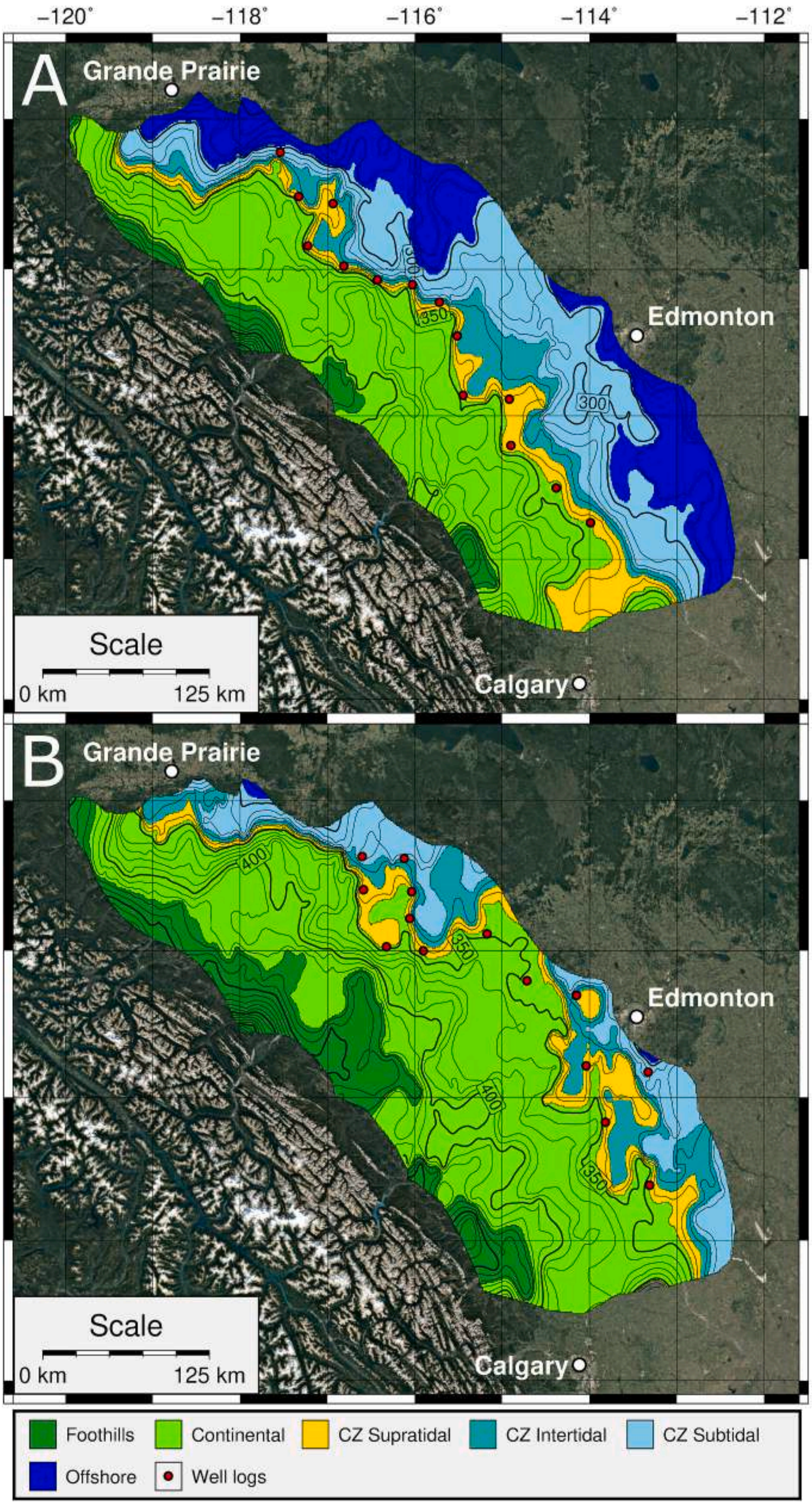


Fig. 9. Paleogeographic maps of the lower (A) and upper (B) tongue MFS surfaces. The isopachs are from the respective cumulative thickness maps T1 and T2 in Fig. 8. Sediment distribution patterns indicate three adjoining areas: 1 - near the foothills, deposits are dominated by coarse, lenticular or laterally interfingered bodies; 2 - typical alluvial deposits are widespread within continental plains; 3 – distal, flat transitional areas include widespread marine signa-ture of the lower Bearpaw tongue (A). Nearshore environments are likely related to a complex devel-opment of tidal embayments with vast submerged areas (B). Well logs indicated by red dots (listed in Table 1) mark the eastward shift from subaerial to submerged deposition (in gamma ray trends, see text). CZ = Coastal Zone. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2010; Hathway, 2016). However, new data discussed in this study support that major eustatic control, combined with local factors, determined the location of depocenters. Three factors are consistent with the latter interpretation. First, new chronostratigraphic constraints document rapid (600 kyr or less) consecutive T-R cycles; second, no depositional discontinuities have been documented in this interval that, instead, records a gradual shift of lithologies and facies; third, major feeding systems and distribution patterns of sediment remains unaltered throughout the stratigraphic interval. Recent multidisciplinary studies on eustatic sea-level changes during the Cretaceous document similar

Table 1
Reference well logs for this study and the ones used as markers for paleogeographic maps. Well logs marked with an asterisk are not present in our dataset and have been used to further calibrate the depths of the closest available data. Location of reference well logs are indicated with blue dots in Fig. 3. Location of all other reported well logs are indicated with red dots in Fig. 9.

UWI	Marker	Reference	Belly River Group base (m s.l. depth)	Bearpaw MFS Lower tongue (m s.l. depth)	Bearpaw MFS Upper tongue (m s.l. depth)
00/01-11-067-24W5/0	Lower coastal to continental	This study	61.5	364.8	415.8
00/16-30-063-22W5/0	Lower coastal to continental	This study	−144.2	192.7	238.1
00/10-10-063-20W5/0	Lower coastal to continental	This study	−117.6	232.3	267.7
00/08-02-060-22W5/0	Lower coastal to continental	This study	−390.1	−52.5	−9.4
00/16-19-058-19W5/0	Lower coastal to continental	This study	−415.7	−81.0	−36.7
00/09-15-057-17W5/0	Lower coastal to continental	This study	−299.0	38.8	75.8
00/06-04-057-14W5/0	Lower coastal to continental	This study	−226.7	111.5	157.6
00/02-28-055-12W5/0	Lower coastal to continental	This study	−192.0	148.0	181.5
00/06-02-053-11W5/0	Lower coastal to continental	This study	−272.5	65.0	111.8
00/09-18-048-10W5/0	Lower coastal to continental	This study	−485.9	−141.1	−116.0
00/11-02-048-07W5/0	Lower coastal to continental	This study	−285.5	56.2	85.3
00/09-14-044-07W5/0	Lower coastal to continental	This study	−432.9	−97.6	−64.8
00/05-04-041-03W5/0	Lower coastal to continental	This study	−327.3	21.3	52.6
00/10-07-038-28W4/0	Lower coastal to continental	This study	−194.5	153.4	177.2
00/09-14-065-18W5/0	Upper coastal to continental	This study	77.2	355.6	392.6
00/09-12-065-15W5/0	Upper coastal to continental	This study	166.0	462.6	493.0
00/10-35-062-18W5/0	Upper coastal to continental	This study	−45.4	241.4	287.5
00/10-28-062-14W5/0	Upper coastal to continental	This study	26.2	326.0	375.7
02/07-29-060-14W5/0	Upper coastal to continental	This study	−45.2	248.9	292.6
00/06-21-058-16W5/0	Upper coastal to continental	This study	−206.6	102.4	144.4
00/06-08-058-13W5/0	Upper coastal to continental	This study	−137.2	160.3	205.5
00/04-20-059-08W5/0	Upper coastal to continental	This study	119.3	423.6	466.9
02/12-32-055-05W5/0	Upper coastal to continental	This study	99.0	404.9	438.9
00/12-30-054-01W5/0	Upper coastal to continental	This study	172.7	474.1	509.5
00/10-11-049-01W5/0	Upper coastal to continental	This study	22.5	325.1	358.7
00/10-29-048-23W4/0	Upper coastal to continental	This study	153.8	428.7	466.2
02/14-26-044-27W4/0	Upper coastal to continental	This study	16.5	316.7	358.0
00/13-30-039-23W4/0	Upper coastal to continental	This study	63.6	356.8	408.1
00/07-12-025-25W4/0	Reference well log	Catuneanu et al. (1997)	No Data	437.1	482.5
00/10-04-065-02W6*	Reference well log	Jerzykiewicz (1997)	−194.4	No Data	No Data
00/06-02-056-19W5	Reference well log	Jerzykiewicz (1997)	−524.4	No Data	No Data
00/12-12-047-09W5	Reference well log	Jerzykiewicz (1997)	−436.5	No Data	No Data
00/04-15-060-06W6	Reference well log	Jerzykiewicz (1997)	−658.2	No Data	No Data
00/07-04-053-24W5*	Reference well log	Jerzykiewicz (1997)	−1068.5	No Data	No Data
00/08-34-044-13W5	Reference well log	Jerzykiewicz (1997)	−866.7	No Data	No Data
00/06-03-033-06W5	Reference well log	Jerzykiewicz (1997)	−759.3	No Data	No Data
00/14-02-042-18W4/0	Reference well log	Eberth and Braman (2012)	No Data	595.6	624.4
00/09-11-042-25W4/0	Reference well log	Eberth and Braman (2012)	No Data	351.1	397.1
00/10-07-038-28W4/0	Reference well log	Eberth and Braman (2012)	No Data	153.4	177.2

events (i.e. Schlanger et al., 1981; Miller et al., 2003; 2004, 2011; Haq, 2014 and references therein). Haq (2014) reports two globally docu-mented transgressive-regressive cycles that appear to match with the age of the studied succession: the first roughly between 75.4 and 73.6 Myr (KCa6) and the second approximately between 73.6 and 72 Myr (KCa7; see also Miller et al., 2003; 2004). The paleogeographic evolu-tion of the Alberta basin discussed in this study also raises hypothesis concerning the occurrence of mature hydrocarbons in post-Bearpaw units, as they may have bypassed the relatively thin Bearpaw seal and, thus, might be trapped in the Horseshoe Canyon Formation (including the Strathmore Member). However, to date, coalbed methane and water have been found in large quantities within the post-Bearpaw reservoirs while only small amounts of oil have been extracted from those units. This indicates that the Cardium Formation oils that sourced the Belly River sands have been prevented to migrate upsection in the permeable post-Bearpaw units.

During the Bearpaw T-R cycles, lower accumulation rates characterize the northwestern and southeastern margin of the study area (Fig. 8), suggesting locally persistent marine conditions throughout the studied time interval.

Given the occurrence of large channelized fluvial systems within the Belly River Group, such areas may represent a primary target for future prospective activities. The eustatic controls on the deposition of the Bearpaw cycles shed new light on how such controls can be discussed in foreland marine and non-marine successions as effective on hydrocar-bon migration and accumulation.

6. Conclusions

Data presented in this study extend the available information on the nature and geographic extent of the Western Interior Seaway in west-central Alberta. This 3D analysis of transgressive-regressive (T-R) cycles documents the reciprocal architecture of marine and non-marine environments with an unprecedented resolution for the Cretaceous. The lower Bearpaw cycle records a rapid transgressive event that lasts ~200 kyr. The upper Bearpaw cycle shows a longer duration of approximately 600 kyr and records a minor rise of the base level. The inferred paleogeography for this interval remained relatively stable compared to the major evolution it underwent during the progradation of the Strathmore Member. During this T-R cycle residual marine conditions seem to persist only in southern Alberta and to the north-west in the Grande Prairie region. The rapid drowning associated with the lower Bearpaw cycle transgression above the channel and delta systems of the uppermost Belly River units, provided an efficient seal and thus played a key role in the formation of the most oil-productive reservoirs within the Belly River Group. In this setting, the Bearpaw Formation represented the sole and final event of marine sedimentation related to the Western Interior Seaway in Alberta, likely occurring because of a major eustatic control rather than tectonic deformation at the observed timescale. In fact, the documented Bearpaw T-R cycles do not show depositional discontinuities, but rather a record of a gradual, eastward shift of the shoreline.

The paleogeographic evolution and the inferred distribution of the

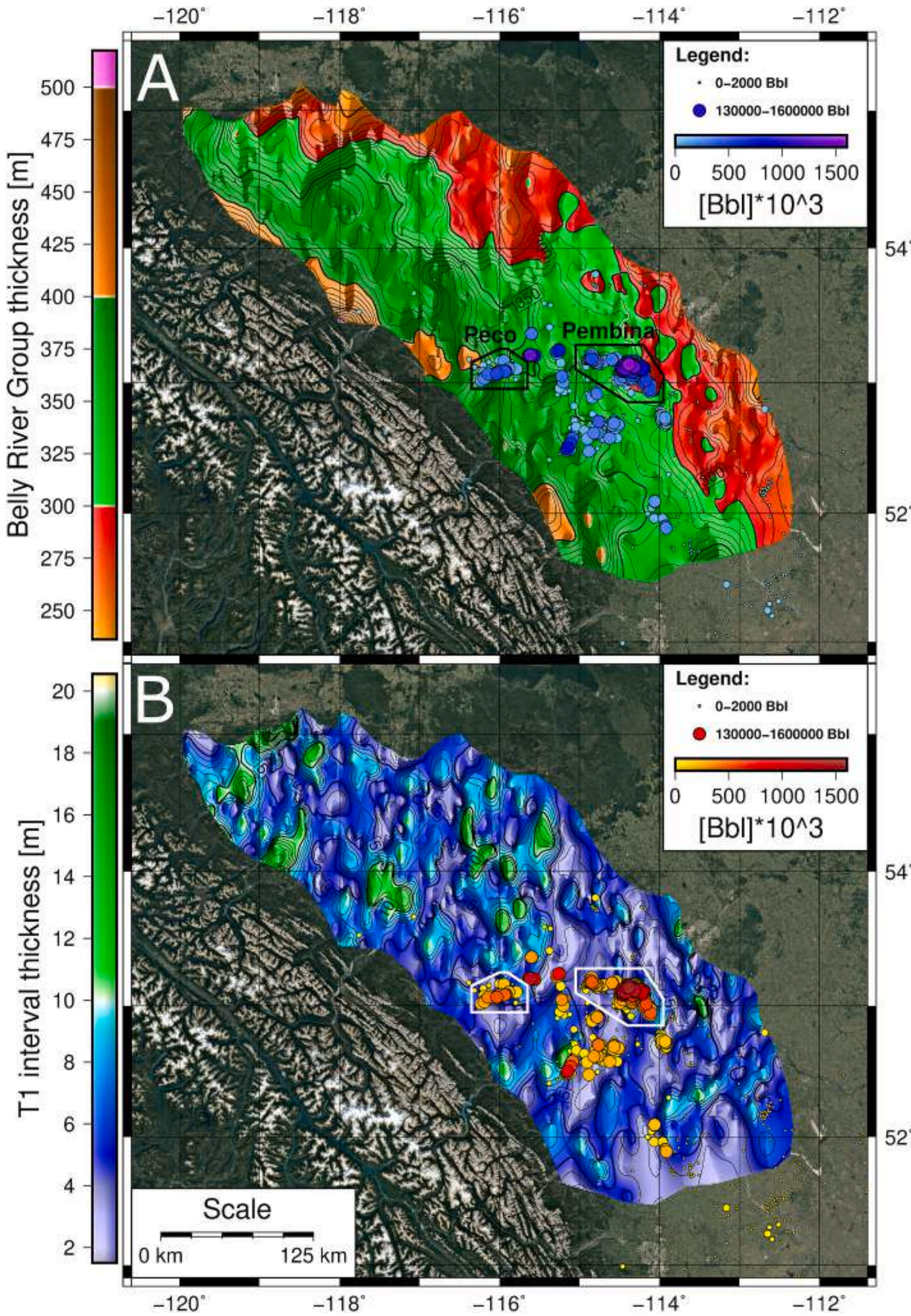


Fig. 10. Productive oil fields from the Belly River Group in Alberta. Shaded relief illumination is doubled to emphasize the geometry of deposits, light comes from northeast and from southeast. Wells are plotted on the isopach maps of (A) the Belly River group (see Fig. 6A) and (B) Bearpaw lower tongue transgressive (T1) interval (see Fig. 6B). Color and size of dots (wells) are proportional to oil exploitation (see legend). Palette color-bars for respective thick-ness intervals are reported on the left in meters. Peco and Pembina East oil fields are indicated. The exploited area in A corresponds to channel-delta lobe systems and is overlain by 2–6 m of T1 interval's fine- grained sediments (B) interpreted as the effective sealing for the oil that migrated from the Cardium Formation into the Belly River Group reservoirs. These Bearpaw transgressive fine-grained deposits prevented further upsection migration into basal channel systems of the Edmonton Group. (For inter-pretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

environments in the study area developed with a NW-SE oriented axis, external to the deformed foothills region of the Canadian Rocky Mountains fold and thrust-belt. The geometry of the foreland basin was inherited by flexural subsidence that provided the accommodation space for the deposition of mainly continental successions from the base of the Belly River Group (at approximately 80 Myr) up to the Tertiary. Sediment accumulation in the study area is linked to primary sources located in the rising cordillera throughout the entire studied interval. Major feeding systems and sediment distribution patterns remained almost unaltered throughout the studied stratigraphic interval, further supporting a gradual trend toward an overfilled foreland basin.

The methodologic approach presented in this study provides a useful tool to discriminate the interference of external eustatic controls in the evolution of a foreland basin.

CRediT authorship contribution statement

Riccardo Zubalich: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Rossella Capozzi:** Supervision, Conceptualization, Project administration, Visualization, Writing - review & editing. **Federico Fanti:** Supervision, Conceptualization, Project administration, Visualization, Writing - review & editing. **Octavian Catuneanu:** Supervision, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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