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The "Judith River–Belly River problem" revisited (Montana-Alberta-Saskatchewan): New perspectives on the correlation of Campanian dinosaur-bearing strata based on a revised stratigraphic model updated with CA-ID-TIMS U-Pb geochronology

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ABSTRACT

Terrestrial strata of the Judith River–Belly River wedge, widely exposed in the plains of north-central Montana, southern Alberta, and southwestern Saskatchewan, were pivotal in early stratigraphic investigations of the Western Interior of North America and are renowned to this day for their spectacular preservation of Late Cretaceous fossils, most notably dinosaurs. Correlation of the Judith River Formation in Montana with the Foremost, Oldman, and Dinosaur Park Formations (= Belly River Group) in Canada has been challenging for a variety of reasons, including lithostratigraphic complexities, legacy bentonite ages of limited comparability, and distinctly different stratigraphic models on opposite sides of the international border. An updated model calibrated with U-Pb zircon ages provides an improved framework for stratigraphic analysis. New geochronology indicates that the Oldman–Dinosaur Park discontinuity in Dinosaur Provincial Park correlates in age with the mid-Judith discontinuity in the Judith River Formation in Montana, which is interpreted as an expansion surface linked to a major pulse of accommodation and onset of the Bearpaw transgression at ca. 76.3 Ma. The regionally expressed shift in alluvial facies marking the mid-Judith discontinuity can be traced in well logs from Montana to southern Canada, where it loses distinction and transitions to a subsurface signature typical of the Oldman–Dinosaur Park discontinuity, which in turn can be traced north to Dinosaur Provincial Park and beyond. Across this expanse, both discontinuities parallel the Eagle/Milk River shoulder at approximately the same stratigraphic height, confirming their chronostratigraphic significance. These findings have clear implications for regional correlation and the evolution of alluvial depositional systems in a foreland basin setting, and they afford an opportunity to evaluate existing interpretations and advance understanding of the stratigraphy and paleontology of the Judith River–Belly River wedge. The term "Judith River–Belly River discontinuity" should be used henceforth to refer to the chronostratigraphically significant stratal discontinuity that subdivides the Judith River–Belly River wedge throughout the plains of north-central Montana, southern Alberta, and southwestern Saskatchewan.

INTRODUCTION

Upper Cretaceous strata in the northern Great Plains have long been fertile ground for discovery and research, and pioneering geologists in both the United States and Canada toiled in the latter half of the 1800s and early 1900s to document and decipher basic patterns of sedimentation in the region. They focused much of their work in the Upper Missouri River, Milk River, and South Saskatchewan River drainage basins, which include expansive outcrop belts of Cretaceous rock in north-central Montana and southern Canada (Alberta and Saskatchewan). Most work targeted Campanian strata, specifically the units referred to today as the Judith River Formation and the Belly River Group (Foremost, Oldman, and Dinosaur Park Formations), presumably for reasons of outcrop accessibility and spectacular fossil richness. Waage (1975) provided a detailed narrative of this seminal stratigraphic undertaking, which he contended led to an improved understanding of the facies concept among North American geologists. In his treatment of this formative period in North American geology, Waage (1975, p. 55) identified the "Judith River–Belly River problem" as the driving impetus behind the work, and this "problem" instigated lively conversation and debate among geologists and paleontologists for decades (e.g., Meek and Hayden, 1856; Cope, 1871; Hatcher and Stanton, 1903; Stanton and Hatcher, 1905; Peale, 1912; Bowen, 1915; Russell and Landes, 1940; McLean, 1971; among others).

This region of the northern Great Plains still attracts considerable attention from geologists and paleontologists, largely due to its hydrocarbon reserves and its amazingly rich dinosaur fossil record (Molenaar and Rice, 1988; Porter, 1992; Smith et al., 1994; Weishampel et al., 2004). Yet, to this day, some lingering confusion and debate remain with regard to the subdivisions and correlation of Campanian strata in the region (McLean, 1971; Jerzykiewicz and Norris, 1994; Hamblin and Abrahamson, 1996): the "Judith River–Belly River problem" persists. We contend that this situation reflects several confounding factors. One is the proliferation of terminology, both formal and informal, that differs across the international boundary. Another is the dependence on age models that are derived from radioisotopic data (K-Ar, $^{40}Ar/^{39}Ar$, U-Pb) produced over the span of

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Figure 1. Generalized outcrop belt of the Judith River Formation (JRF) in Montana and the Belly River Group (BRG) in the plains of Alberta and Saskatchewan, Canada. Upper portions of the Two Medicine Formation (TMF) represent the updip equivalent of the Judith River Formation in northwestern Montana. Focal areas include the expansive outcrops along the Missouri River in the Upper Missouri River Breaks National Monument (UMRBNM), exposures in the Milk River drainage in northern Montana (KC—Kennedy Coulee) and southeastern Alberta (Of—Onefour area), and exposures in the Red Deer River valley in Dinosaur Provincial Park (DPP). Figure is modified from Eberth and Hamblin (1993).

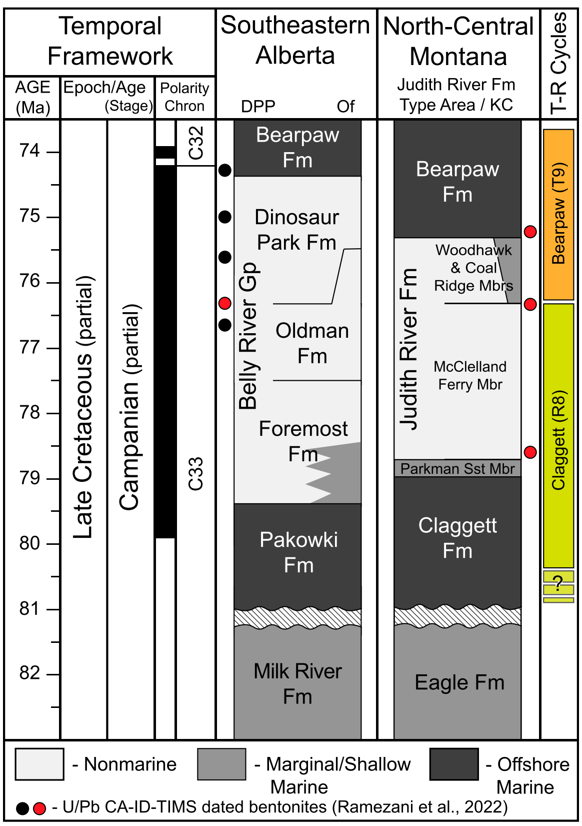


Figure 2. Chronostratigraphic chart of Campanian strata in north-central Montana and southeastern Alberta (modified from Ramezani et al., 2022). The stratigraphy of recently published U-Pb zircon ages in the Judith River Formation, Bearpaw Formation, and Belly River Group (Ramezani et al., 2022) is indicated in relation to key units with black and red circles. The four ages specifically referenced in this study (Table 1) are indicated with red circles. The chronostratigraphy of the Pakowki, Claggett, Milk River, and Eagle Formations and the approximate duration of a hiatus in southeastern Alberta and north-central Montana are based on Payenberg et al. (2002, 2003). DPP—Dinosaur Provincial Park; Of—Onefour area, Alberta, Canada; KC—Kennedy Coulee; T-R—transgressive-regressive; Fm—Formation; Gp—Group; Mbrs—Members; Sst—Sandstone; CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry.

decades in different laboratories using different analytical approaches. Arguably, another challenge is the recent emphasis on fine-scale chronostratigraphic subdivision and correlation of the terrestrial sedimentary record, largely driven by the aims of dinosaur paleontologists attempting to delimit stratigraphic ranges of taxa in order to test evolutionary and paleobiogeographic hypotheses (Evans et al., 2009; Fricke et al., 2009; Mallon et al., 2012; Fowler, 2017; Lowi-Merri and Evans, 2020). These confounding factors, among others, are also currently framed in the context of two fundamentally different stratigraphic models on opposite sides of the international border (Eberth and Hamblin, 1993; Rogers, 1995, 1998; Eberth, 2005; Rogers et al., 2016).

In this study, we reviewed the current stratigraphic models for the Judith River Formation in Montana and the Belly River Group in southern Alberta and Saskatchewan (Figs. 1 and 2). Our primary goal was to advance understanding of these important stratigraphic units, specifically in relation to their lithostratigraphic and chronostratigraphic correlation across the plains of Alberta, Saskatchewan, and Montana. To achieve this goal, we used an updated chronostratigraphic framework based on a suite of internally consistent chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) U-Pb analyses of select bentonite beds across the Western Interior recently reported in Ramezani et al. (2022). With new age calibrations and a comprehensive understanding of the regional stratigraphy based on surface sections linked with expansive subsurface well-log data sets, we evaluated the existing framework of correlation, and we propose a revised stratigraphic model that addresses long-standing uncertainties.

GEOLOGICAL BACKGROUND

Judith River–Belly River Wedge in Context

The Judith River–Belly River clastic wedge accumulated in the Western Interior Basin, an expansive retroarc foreland basin that hosts a thick sequence of complexly interbedded terrestrial and marine strata ranging in age from Jurassic to early Cenozoic (Kauffman, 1977; Kauffman and Caldwell, 1993; DeCelles and Currie, 1996; DeCelles, 2004; Miall et al., 2008; Fuentes et al., 2009). Tectonism occurred in pulses and waves with intermittent periods of relative quiescence (e.g., Cant and Stockmal, 1989; Heller et al., 1988), and episodes of thrust-sheet stacking and loading in the active Cordillera rejuvenated source areas and drove subsidence in the genetically coupled basin. Subsidence was asymmetric in nature and was focused in proximal reaches of the basin, in proximity to the advancing thrust sheets (Beaumont, 1981; Jordan, 1981; Beaumont et al., 1993). Uplifted source terranes in the thrust belt and more local volcanic centers supplied abundant siliciclastic and volcaniclastic detritus to vast alluvial plains that drained to marginal-marine and open-marine environments of the Western Interior Seaway. Resultant patterns in sedimentation were complex and reflect the dynamic interplay among tectonic subsidence, sediment supply (and evolving sediment delivery systems), eustasy, and latitudinal variations in climate (e.g., Kauffman, 1977; Heller et al., 1988; Jerzykiewicz and Sweet, 1988; Cant and Stockmal, 1989; Leckie and Smith, 1992; Eberth and Hamblin, 1993; Eberth and Braman, 2012; among many others). Explosive volcanic events in the Cordillera generated copious air-fall deposits of vitric ash, and the altered remnants of these ash beds, represented in the rocks by bentonites, have made it feasible to radioisotopically calibrate much of the Western Interior record, especially during the Late Cretaceous.

The Judith River–Belly River clastic wedge is recognized as one of six stratigraphically discrete eastward-thinning clastic tongues of predominantly terrestrial strata in the southern Canada and Montana portion of the Western Interior foreland basin (Cant and Stockmal, 1989; Stockmal et al., 1992; Miall et al., 2008). The wedge was deposited during a major regressive-transgressive cycle of the Western Interior Seaway (R8-T9 of Kauffman, 1977), over a span of ~6–7 m.y. in the mid to late Campanian (Hamblin and Abrahamson, 1996; Gale et al., 2020; Ramezani et al., 2022). Judith River–Belly River sedimentation commenced with the retreat of the Claggett (Pakowki) sea, which began shortly after ca. 81 Ma (Hamblin and Abrahamson, 1996; Rogers, 1998; Payenberg et al., 2002, 2003; Mumpy and Catuneanu, 2019). For the next ~4 m.y., shorelines in the Montana-Alberta-Saskatchewan region shifted seaward (eastward) under conditions of both normal and forced regression, as evidenced by vertically stacked and offlapping successions of incised shoreface deposits in the Foremost Formation across southernmost Alberta and the erosional base of the Parkman Sandstone Member in north-central Montana (Gordon, 2000; Rogers et al., 2016). The onset of the Bearpaw transgression in central Montana commenced ca. 76.3 Ma and was heralded by deposition of the shallow-marine Woodhawk Member of the Judith River Formation in the type area (Rogers et al., 2016). Throughout southeastern Alberta and western Saskatchewan upper portions of the Dinosaur Park Formation (Lethbridge coal zone) and the Bearpaw Formation interfinger, with marine shales resting on coalified peat beds (Eberth, 2005). In localized instances in southeastern Alberta, marine shales exhibit lateral continuity with mud-filled incised valleys (paleochannels) of tidal and estuarine origin (Eberth, 1996). The leading edge of the advancing Bearpaw sea migrated westward toward the orogenic front for the next ~2.6 m.y. (Eberth and Kamo, 2020), presumably in response to accommodation driven by tectonic subsidence. Based on the age estimates outlined above, and from a purely temporal perspective, approximately two thirds of Judith River–Belly River deposition transpired during a regressive phase of the Western Interior Seaway. The final ~2.6 m.y. of Judith River–Belly River deposition occurred during the Bearpaw transgression (Fig. 2). Asymmetry in depositional history is paralleled by the relative thickness of the strata that accumulated during these two distinct phases of sedimentation in the basin, with the regressive record being considerably thicker than overlying transgressive deposits.

Lithostratigraphic Overview

McLean (1971) compiled a detailed historical overview of the nomenclatural complexity that characterizes the Montana-Alberta-Saskatchewan Campanian record, and the relevant aspects of his review are summarized here and updated with a few recent lithostratigraphic endeavors. Work with nomenclatural import came first in Montana with the pioneering efforts of Hayden (1871), who proposed the term “Judith group” in reference to strata exposed near the confluence of the Judith and Missouri Rivers. Meek (1876) subsequently introduced the term “Judith River group” for these same strata. Stanton and Hatcher (1905), working throughout north-central Montana and select parts of southern Alberta, concluded that the “Judith River beds” rested between the underlying “Claggett formation” and overlying “Bearpaw shales” and relegated Judith River strata to the previously established Montana Group of Eldridge (1888, 1889). The term “Judith River Formation” began to appear in the literature in the early 1900s (e.g., Lambe, 1907; Knowlton, 1911; Peale, 1912; Stebinger, 1914; Bowen, 1915, 1920), and it has been employed in a formal sense for more than a century to refer to strata intercalated between the Claggett and Bearpaw Formations in Montana and the Pakowki and Bearpaw Formations in Canada (e.g., Weimer, 1960, 1963; Ostrom, 1964; McLean, 1971, 1977; Sahni, 1972; Case, 1978; Wood et al., 1988; Wood, 1989; Brinkman, 1990; Eberth, 1990; Thomas et al., 1990). Sahni (1972) proposed a composite stratotype for the Judith River Formation based on two sections measured along Birch Creek, in the western portion of the type area.

Four formal members are recognized in the Judith River Formation within Montana. The Parkman Sandstone Member, first identified in exposures in the Powder River Basin in northern Wyoming (Darton, 1906; Knechtel and Patterson, 1956), and correlated to the north into central Montana by Gill and Cobban (1973), has long been recognized as a distinctive sandstone deposit of shallow-marine origin at the base of the formation. More recently, three new members were formalized in the type area of the Judith River Formation in the Upper Missouri River Breaks National Monument by Rogers et al. (2016). Two of the new members, namely, the McClelland Ferry Member and Coal Ridge Member, are terrestrial in nature, and both crop out widely within the type area and beyond. The third newly defined member, the Woodhawk Member, consists of distinctive shallow-marine sandstone deposits, and it is well exposed in the upper half of the formation in the eastern portion of the Upper Missouri River Breaks National Monument.

The path to nomenclatural clarity and stability has been more arduous in the plains of southern Canada, where Dawson (1883, 1884) first introduced the term “Belly River series” for strata exposed along the Oldman River in southern Alberta. McConnell (1885) and Tyrrell (1887) extended Dawson’s terminology to correlative strata in east-central Alberta and Saskatchewan. In the early 1900s, the original incarnation of the Belly River series was infused with several subunits, including the Milk River Sandstone (Eagle equivalent), Pakowki Formation (Claggett equivalent), Foremost Formation, and the Pale beds (Dowling, 1916, 1917; Allan, 1919; Slipper, 1919). In an effort to bring the lithostratigraphy more in line with Dawson’s (1883, 1884) original intention, Williams and Dyer (1930) restricted their “Belly River Formation” to include only the continental strata above the marine Pakowki Formation and below the marine Bearpaw Formation. This revision relegated the Pale beds and Foremost Formation to member status within the Belly River Formation. Russell and Landes (1940) subsequently argued for dropping the “ambiguous” term “Belly River series” (or Belly River Formation) in the plains of southern Alberta and proposed instead to elevate the Foremost to formation rank, and to do the same with the overlying “Pale beds,” which they renamed the “Oldman Formation.” Taken together, and in the context of bracketing marine units, the Foremost and Oldman Formations of Russell and Landes (1940) are stratigraphically equivalent to the Judith River Formation in Montana.

McLean (1971, 1977) made a case to employ the term "Judith River Formation" in lieu of "Belly River," "Foremost," and "Oldman" in southern Alberta (with the exception of the foothills region west of the Sweetgrass arch) and Saskatchewan due to precedence in usage and ambiguity in the definitions of the Foremost and Oldman Formations (both units lack type sections and can be difficult to distinguish in outcrop). Subsequently, most paleontologists and non-petroleum-industry geologists on both sides of the international boundary tended to use the term "Judith River Formation" to refer to the predominantly terrestrial strata of Campanian age that yield abundant dinosaurs and other fossils (e.g., Dodson, 1983, 1987; Thomas et al., 1987, 1990; Wood et al., 1988; Wood, 1989; Brinkman, 1990; Eberth, 1990; Eberth et al., 1990). However, in the early 1990s, Eberth and Hamblin (1993) proposed that the Judith River Formation should be elevated to group rank in both Canada and Montana, and their newly proposed "Judith River Group" included three formations: (1) the Foremost Formation, (2) the Oldman Formation, and (3) the new Dinosaur Park Formation. Extending the nomenclature of Eberth and Hamblin (1993) across the international border into Montana was problematic due to the traditional inclusion of the Judith River Formation within the Montana Group of Eldridge (1888, 1889). The petroleum industry in western Canada accepted the threefold formational stratigraphy of Eberth and Hamblin (1993) but declined to adopt the elevation in rank of the Judith River Formation, opting instead to maintain reference to the long-standing Belly River "series," which was formalized to group status by Jerzykiewicz and Norris (1994). As a result, Hamblin and Abrahamson (1996) concluded that the term "Judith River Group" should be abandoned, and that "Belly River Group" should be resurrected and used throughout the plains (and foothills) of southern Alberta and Saskatchewan to refer to strata bounded by the Pakowki/Lea Park and Bearpaw Formations. In its current construal, the Belly River Group includes three formations in the plains of southern Alberta and Saskatchewan: Foremost, Oldman, and Dinosaur Park. In the foothills region of Alberta, the Belly River Group includes the Connelly Creek, Lundbreck, and Dinosaur Park/Drywood Creek Formations (Jerzykiewicz and Norris, 1994; Hamblin and Abrahamson, 1996).

Last, in addition to the array of formal nomenclature detailed above, there is currently a suite of terminology linked to informal coal and sandstone zones in the Belly River Group. These include the McKay, Taber, and Lethbridge coal zones and the Herronton and Comrey sandstone zones (for a detailed overview, see Eberth, 2005).

CONUNDRUMS OF CAMPANIAN CORRELATION—PAST AND PRESENT

Correlation of the Judith River–Belly River wedge proved to be a challenge in the early days of stratigraphic inquiry in the "interior Cretaceous" section, and Waage's (1975) lively review provides the historical backstory of foibles, conceptual breakthroughs, and eventual progress. Indeed, geologists had to first appreciate the large-scale pattern of transgressive and regressive cycles of sedimentation before meaningful progress could be made. Additional insights, particularly in relation to the relative ages of the strata in question, hinged upon the discovery of age-informative invertebrate and vertebrate fossils, which are abundant in the Judith River–Belly River wedge. By the early 1900s, with a suite of documented local sections and age-diagnostic fossils in hand, the broad regional stratigraphy of the Judith River–Belly River wedge was understood (Stanton and Hatcher, 1905), and accurate correlation at the formation scale among outcrop belts distributed across the plains of Montana and southern Alberta and Saskatchewan was possible.

Current questions of a stratigraphic nature in the Judith River–Belly River wedge are generally focused at a much finer scale of resolution, and these are driven to some extent by the research goals of paleontologists who seek to place their fossil discoveries (often dinosaurs) in temporal and paleoenvironmental context and compare them with other known sites across the region. One obvious obstacle to finer-scale correlation within the wedge, and communication in general as it relates to the geology of the Judith River–Belly River wedge, has been the abundance of formal and informal lithostratigraphic terminology in play. Cogent arguments of stratigraphic placement and correlation are founded on the understanding of the bodies of rock in question, and when the lithostratigraphic nomenclature itself is regionalized, historically complicated, or in flux, articulating associations and connections can be difficult. Importantly, the opposite condition can be problematic too, especially if higher-resolution correlation is the goal. Prior to the recent establishment of three new formal members in the Judith River Formation in Montana (Rogers et al., 2016), this largely undifferentiated unit was difficult to contextualize and correlate at a level more refined than the formation-scale itself, particularly to the many distinct named units in the Belly River Group of Alberta and Saskatchewan.

A second complicating factor has been the lack of formal stratotypes and reference sections for some of the key units within the Judith River–Belly River wedge. For example, despite their unquestionable significance in the annals of Canadian geology and paleontology, there has never been a type section designated for either the Foremost Formation or the Oldman Formation (McLean, 1977). This is not entirely unexpected given the history of these classic units: they were named long before modern lithostratigraphic practice. Both units were originally defined in outcrop by Russell and Landes (1940) and redefined in part by Eberth and Hamblin (1993) in the Dinosaur Provincial Park area. Furthermore, their upper and lower contacts were illustrated in two reference geophysical logs by Macdonald et al. (1987). Nevertheless, in the absence of formal definitions and detailed lithologic descriptions tied to accessible surface sections, it remains difficult to identify consistent contacts for both formations.

Another complication with regard to correlation has been the use of informal units and marker beds, some with potential chronostratigraphic significance, including three named coal zones (McKay, Taber, Lethbridge; Crockford, 1949) and two named sandstone zones (Herronton and Comrey). At the local scale, this approach is certainly reasonable, as has been demonstrated for the Lethbridge coal zone within Dinosaur Provincial Park. However, over longer distances and at a regional scale, and especially along depositional dip, coaly intervals that represent ancient coastal plain mires should track shoreline deposits (e.g., Flores et al., 1984) and thus may assume a diachronous distribution across the broader region. For example, in the Dinosaur Provincial Park area, a bentonite intercalated at the base of the Lethbridge coal zone near the top of the Dinosaur Park Formation is now dated by the U-Pb zircon method to 75.017 ± 0.020 Ma (Ramezani et al., 2022). In the badlands of the Upper Missouri River Breaks National Monument, the lithological equivalent of the Lethbridge coal zone at the top of Judith River Formation (Rogers et al., 2016, their fig. 2) is definitively older than 75.219 ± 0.031 Ma, based on a new bentonite zircon age at the base of the overlying Bearpaw Formation (Table 1; Ramezani et al., 2022).

Two zones of unusual sandstone abundance (anomalously thick or clustered sandstone bodies) have also been identified and used in recent years to subdivide formal units, link isolated outcrop belts, and place fossil occurrences in context (Troke, 1993; Eberth, 2005; Ryan et al., 2010; Evans and Ryan, 2015; Freedman Fowler and Horner, 2015; Cullen and Evans, 2016; Mallon et al., 2016; Ryan et al., 2017). Specific

TABLE 1. U-Pb (ZIRCON) CA-ID-TIMS GEOCHRONOLOGY FROM NORTH-CENTRAL MONTANA AND SOUTHERN ALBERTA*

Sample name	Formation/Member	Locality		Reported age (Ma)	Internal error (±2σ)
		Latitude (°N)	Longitude (°W)		
North-central Montana					
PPF1-03	Bearpaw Fm. (basal)	47°43′29.2″	108°56′36.7″	75.219	0.031
ST1-03	JRF/McClelland Ferry Mbr.	47°45′37.2″	109°19′46.9″	76.329	0.035
KC061517-1	JRF/McClelland Ferry Mbr.	48°56′58.5″	110°36′09.3″	78.594	0.024
Southern Alberta					
JC082817-1	Dinosaur Park Fm.	50°45′05.5″	111°24′33.4″	76.354	0.057

Notes: CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry; Fm.—Formation; JRF—Judith River Formation; Mbr.—Member. The ST1-03 bentonite is closely associated with the mid-Judith discontinuity in the Upper Missouri River Breaks National Monument, and the JC082817-1 bentonite is closely associated with the Oldman–Dinosaur Park discontinuity in Dinosaur Provincial Park (see text for more details). The PPF1-03 bentonite occurs ~5 m above the base of the Bearpaw Formation in the Upper Missouri River Breaks National Monument (Rogers et al., 2016). The KC061517-1 bentonite in the Kennedy Coulee field area is intercalated near the top of the "marker A coal" (Goodwin and Deino, 1989) near the base of strata equivalent to the McClelland Ferry Member of the Judith River Formation (Fig. 1). Decay constants from Jaffey et al. (1971).

*From Ramezani et al. (2022).

reference is made to the Herronton sandstone zone (e.g., Eberth, 2005), a sandy interval of variable expression above the Taber coal zone (see above) at the top of the Foremost Formation (but see Cullen et al. [2016], who considered the Herronton sandstone to be a basal unit of the Oldman Formation), and the Comrey sandstone zone (or Comrey member; Troke, 1993), an interval of stacked sandstone beds that occurs in the approximate middle of the Oldman Formation (Russell and Landes, 1940; Hamblin, 1994, 1997; Hamblin and Abrahamson, 1996; Eberth, 2005). As with the aforementioned coal zones, at the local scale, these lithologic markers prove useful, but determining whether these sandstone "zones," which vary in outcrop and subsurface expression (e.g., Hamblin, 1994, 1997; Freedman Fowler and Horner, 2015), truly have chronostratigraphic significance and are thus useful for regional correlation remains to be fully evaluated. Importantly, in the type area of the Judith River Formation in the Upper Missouri River Breaks National Monument, where the Judith River Formation is exposed in its entirety, surface sections and well logs that span the McClelland Ferry Member (Oldman Formation equivalent) exhibit no readily discernible patterning with regard to the thickness or clustering of fluvial sandstone bodies (see also Hamblin, 1997). Thick sandstone bodies with sheet-like geometries are distributed throughout the McClelland Ferry Member and are therefore best suited for characterizing and correlating the unit as a whole (sensu Rogers et al., 2016).

A major confounding factor that without question has hindered high-resolution regional correlation of the Judith River–Belly River wedge is legacy radioisotopic ages with limited comparability that have accrued over decades. Since the initial K-Ar efforts of Folinsbee et al. (1961), geologists have used different chronometers and methodologies (K-Ar, $^{40}Ar/^{39}Ar$, U-Pb ID-TIMS, U-Pb secondary ion mass spectrometry [SIMS]) applied to different minerals (biotite, sanidine, plagioclase, and zircon) to produce bentonite ages of highly variable vintages in the Judith River–Belly River wedge (e.g., Lerbekmo, 1963; Goodwin and Deino, 1989; Thomas et al., 1990; Eberth et al., 1992; Eberth and Hamblin, 1993; Obradovich, 1993; Rogers et al., 1993, 2016). This has led to confounding mixtures of age data that render correlation difficult, at least with precision or confidence among units. Fortunately, we now have a set of modern and internally consistent CA-ID-TIMS U-Pb zircon ages over a wide geographic distribution upon which chronostratigraphic frameworks can be constructed and unambiguous temporal correlations can be made, both in the current study interval (Judith River–Belly River) and beyond (Beveridge et al., 2022; Ramezani et al., 2022).

A TALE OF TWO DISCONTINUITIES

One final obstacle to correlation within the Judith River–Belly River wedge has been the existence of two distinctly different stratigraphic models on opposite sides of the international border (Eberth and Hamblin, 1993; Rogers, 1995, 1998; Eberth, 2005; Rogers et al., 2016). These two models, which are founded on stratigraphic discontinuities of distinctly dissimilar nature, have complicated efforts to resolve lithostratigraphic and chronostratigraphic relationships in the region.

Oldman–Dinosaur Park Discontinuity

In Canada, geologists and paleontologists have generally followed the stratigraphic model of Eberth and Hamblin (1993). In their model, the Belly River Group is subdivided into three units: the Foremost, Oldman, and Dinosaur Park Formations (Fig. 2). A widespread discontinuity is embedded between the Oldman and Dinosaur Park Formations. This discontinuity, herein referred to as the Oldman–Dinosaur Park discontinuity, exhibits considerable relief locally (up to 30 m) and expresses ~1.5 m.y. of diachroneity across the region from Dinosaur Provincial Park south to Onefour, Alberta (Eberth and Hamblin, 1993; Eberth, 2005). It is interpreted to climb stratigraphically and thereby become younger to the south and southeast, toward Saskatchewan and the international border with Montana (Fig. 3A). Due to the diachronous nature of its basal contact, the Dinosaur Park Formation is interpreted to thin to the south, with the unit attaining a thickness of ~80 m in the Dinosaur Provincial Park area and thinning to ~30 m along the international border in southeasternmost Alberta. The unit is observed to thicken to ~120 m at Edmonton, where the Bearpaw Formation pinches out. Eberth and Hamblin (1993, p. 194) concluded that the Oldman Formation is "lithostratigraphically identical to the type strata of the Judith River Group along the Missouri River," thus implying that the Dinosaur Park Formation may pinch out completely in northern Montana (south of Havre) before reaching the vicinity of the Judith River Formation type area along the Missouri River in the Upper Missouri River Breaks National Monument.

Building upon the observations of Williams and Burk (1964) and Jeletzky (1971), Eberth and Hamblin (1993) interpreted the Oldman–Dinosaur Park discontinuity to represent the time-transgressive intersection between two distinctly sourced lobes of alluvial deposits (Figs. 3B and 3C). These two megafan-scale depositional lobes were interpreted to have migrated in response to the complex interplay among tectonically driven basin subsidence (accommodation), isostatic adjustments, sediment supply dynamics, and an evolving basin topography characterized by an overall southerly tilt. In their tectono-stratigraphic reconstruction (see also Eberth, 2005), they posited that the Dinosaur Park lobe, which was sourced in the Omineca belt in the northern portion of the Canadian Cordillera, migrated southward and eastward over several million years

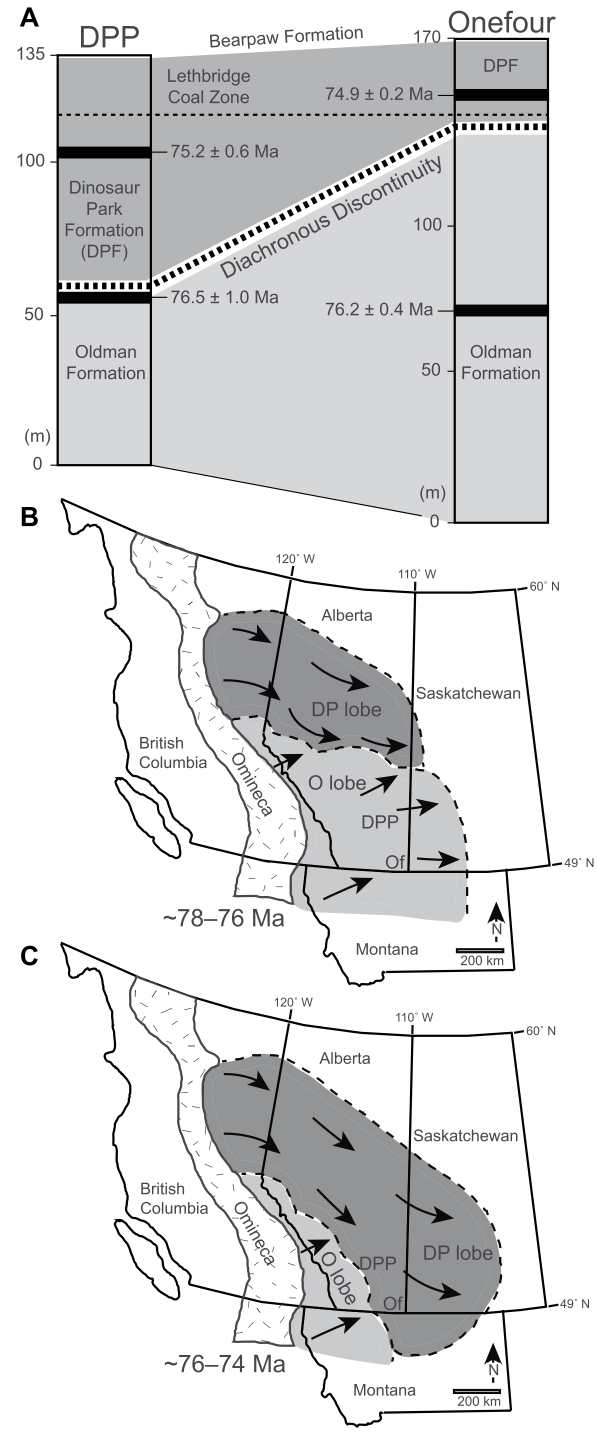


Figure 3. Stratigraphic model of Belly River Group proposed by Eberth and Hamblin (1993). (A) In this model, the Oldman–Dinosaur Park discontinuity is diachronous across its expanse, expressing up to 1.5 m.y. of diachroneity between Dinosaur Provincial Park (DPP) and the Onefour (Of) region in southern Alberta (legacy $^{40}Ar/^{39}Ar$ ages are from Eberth and Hamblin [1993], updated with 2σ errors). (B) Two distinct clastic lobes of alluvial nature fill the basin, with the Dinosaur Park lobe (DP lobe) sourced to the north, and the Oldman lobe (O lobe) sourced to the south. The diachronous discontinuity is interpreted to have developed at the intersection of the two alluvial lobes and is argued to maintain distinction across the region. The Omineca belt is identified as a source terrane for clastics in the basin and likely yielded the extraformational clasts in the Dinosaur Park Formation. (C) Over time, the Dinosaur Park lobe overtopped the Oldman lobe as it built southward and eastward into the basin. Both units are interpreted to have accumulated during R8 (Claggett regression) and T9 (Bearpaw transgression). Arrows in B and C indicate general paleocurrent directions. Figure is modified from Eberth and Hamblin (1993).

following depositional slope, gradually overstepping portions of the Oldman lobe, which was sourced more to the south in northwestern Montana, and which, at least within Alberta and Saskatchewan, migrated in a general northeastward direction. Eberth and Hamblin (1993) envisioned both lobes accumulating concurrently in a variety of alluvial and paralic settings. With regard to regional patterns of regression and transgression, biostratigraphic and radioisotopic data indicate that the southward migration of the Dinosaur Park lobe into southern Alberta occurred during the early stages of transgression of the Bearpaw sea. Deposits of the Oldman Formation are generally considered to have accumulated during regression of the Claggett (Pakowki) sea (Eberth, 2005; Gilbert, 2019; Gilbert et al., 2020), although upper parts of this unit in southeastern Alberta apparently also accumulated during transgression of the Bearpaw sea.

In outcrop, Eberth and Hamblin (1993) placed the Oldman–Dinosaur Park discontinuity at the base of the first sandstone body that exhibits mineralogical and sedimentological characteristics consistent with the Dinosaur Park Formation (e.g., high percentage of smectite clay, immature mineralogy, relatively high plagioclase and low K-feldspar content, large-scale inclined heterolithic stratification). Because these boundary-defining fluvial sandstone bodies are erosionally based, the discontinuity was deemed to be generally disconformable, although no significant hiatus was implied. Where a notable sandstone body deemed characteristic of the Dinosaur Park Formation was absent in local surface sections, the discontinuity was placed within overbank facies based on distinguishing features of both formations (color, weathering patterns, etc.), and it was presumed to be locally conformable (Fig. 4).

In geophysical well logs, Eberth and Hamblin (1993, p. 183) placed the Oldman–Dinosaur Park discontinuity and formational contact at "the first major leftward gamma-ray deflection following a maximum gamma-ray peak or a series of peaks between the Taber and Lethbridge coal zones." Eberth and Hamblin (1993) further concluded that the gamma-ray log was best for picking the discontinuity, and Glombick (2011a, 2011b) concurred, noting that the discontinuity was most readily picked above the informal "upper siltstone member" of the Oldman Formation (Hamblin, 1994, 1997), which is an interval of finer-grained facies developed at the top of the Oldman Formation that typically exhibits several strong gamma-ray peaks relative to underlying and overlying strata. Glombick (2011a, p. 7) further concluded that the formation contact that coincides with the Oldman–Dinosaur Park discontinuity "is best picked using the gamma-ray log exclusively, and other logs, such as density and neutron porosity and resistivity, are unreliable in locating the position of the contact."

Mid-Judith Discontinuity

A different stratigraphic model is in place for the Judith River Formation in Montana, where, based on complete surface sections that span the formation and copious well logs, Rogers et al. (2016) subdivided the terrestrial portion of the Judith River Formation into two members, namely, the McClelland Ferry Member and the superjacent Coal Ridge Member. Their marine Woodhawk Member represents the upper half of the Judith River Formation in the eastern portion of the type area, and it correlates inland and

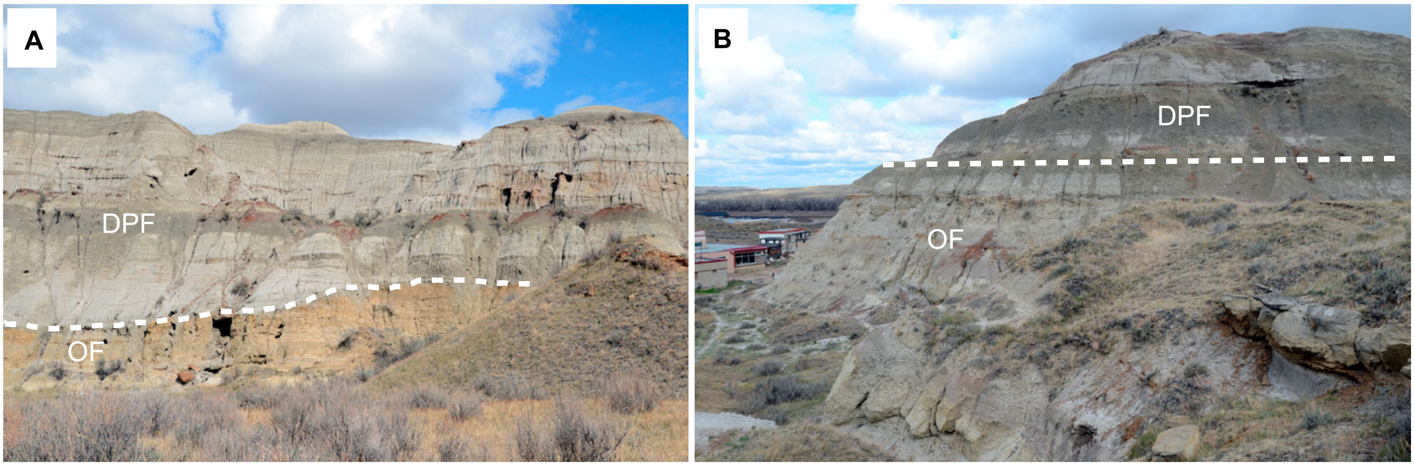


Figure 4. Belly River Group exposures in Dinosaur Provincial Park, Alberta. (A) View of contact between Oldman (OF) and Dinosaur Park (DPF) Formations. Here, the contact (dashed line) is placed at the erosive base of a fluvial paleochannel. (B) Another view of contact between Oldman (OF) and Dinosaur Park (DPF) Formations at the field station. Here, the contact is approximated based on lithological changes as reflected in color and weathering in outcrop. Note change in slope that coincides with approximate formation boundary (dashed line).

updip with the Coal Ridge Member. A widespread stratigraphic discontinuity, designated the mid-Judith discontinuity (Rogers et al., 2016), marks the contact between the McClelland Ferry and Coal Ridge Members in fully terrestrial strata. In the eastern portion of the type area, the mid-Judith discontinuity coincides with the contact between terrestrial strata of the McClelland Ferry Member and overlying marine deposits of the Woodhawk Member (Fig. 5). There is no evidence of erosion or hiatus associated with the mid-Judith discontinuity in terrestrial strata (McClelland Ferry–Coal Ridge contact), and, unlike the Oldman–Dinosaur Park discontinuity described above, the mid-Judith discontinuity is apparently approximately isochronous throughout the region. This interpretation was based on subsurface data in north-central Montana, southern Alberta, and western Saskatchewan, which indicate that the discontinuity essentially parallels the Eagle/Milk River shoulder (Rogers et al., 2016). The Eagle/Milk River shoulder is often used as a regional stratigraphic datum, and it is readily identified on geophysical well logs (most readily in resistivity logs), where it marks the contact between the Eagle Formation and overlying Claggett Formation in Montana and the Milk River Formation and overlying Pakowki Formation in the plains of southern Alberta and Saskatchewan (Payenberg et al., 2002, 2003; Glombick and Mumpy, 2014; Mumpy and Catuneanu, 2019).

The mid-Judith discontinuity was interpreted to have formed in response to a pulse of accommodation in the foreland basin (Rogers, 1998; Rogers et al., 2016), presumably in response to tectonic loading in the overthrust belt and subsidence in the adjacent basin. The abrupt increase in the rate of addition of accommodation outstripped sediment supply in more distal reaches of the wedge, and the Bearpaw transgression ensued, as evidenced by deposition of the marine Woodhawk Member atop the terrestrial McClelland Ferry Member. Added accommodation also impacted terrestrial depositional systems and alluvial architecture in the Coal Ridge Member several tens of kilometers upstream from the advancing shorelines of the Woodhawk Member.

From a sequence stratigraphic perspective, the mid-Judith discontinuity is herein considered an expansion surface (sensu Martinsen

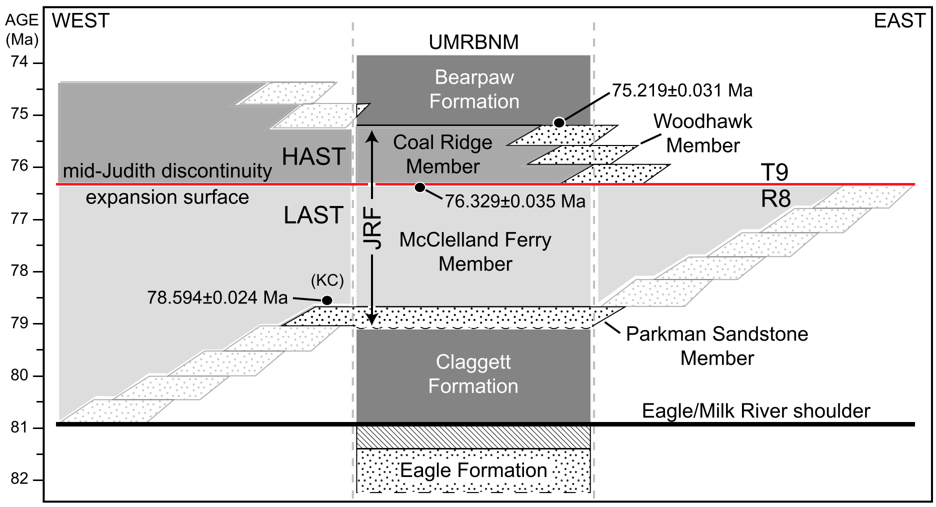


Figure 5. Stratigraphic model of Rogers (1995, 1998) and Rogers et al. (2016), updated with three new ages from Ramezani et al. (2022). In this reconstruction, the mid-Judith discontinuity, which parallels the Eagle/Milk River shoulder, marks the boundary between a low accommodation systems tract (LAST) and a high accommodation systems tract (HAST) in the terrestrial record of the Judith River Formation. The discontinuity, which can be identified in surface exposures and well logs, represents an expansion surface that formed in response to a pulse of added accommodation in the basin. The Parkman Sandstone and McClelland Ferry Members accumulated during the R8 Claggett regressive phase. The Coal Ridge and Woodhawk Members accumulated during the subsequent T9 Bearpaw transgressive phase. KC—Kennedy Coulee, Upper Missouri River Breaks National Monument (UMRBNM).

et al., 1999), which reflects an abrupt increase in the rate of addition of accommodation at the regional scale (Fig. 5). The underlying McClelland Ferry Member represents the low accommodation systems tract, or LAST, and a Bayesian age-stratigraphic model (Ramezani et al., 2022) suggests a rock accumulation rate of 2.43 ± 0.05 cm/k.y. for this unit. The overlying Coal Ridge Member embodies the high accommodation systems tract, or HAST, and data from Ramezani et al. (2022) suggest a rock accumulation rate of 8.57 ± 0.36 cm/k.y. for this unit. This reconstruction of Judith River–Belly River stratigraphy effectively subdivides the wedge in Montana into regressive (McClelland Ferry and Parkman Sandstone Members) and transgressive (Coal Ridge and Woodhawk Members) depositional systems across the mid-Judith discontinuity/expansion surface (Fig. 5).

The position of the mid-Judith discontinuity can be closely approximated to within a few meters in surface exposures (Fig. 6), where it is delimited by a pronounced shift in alluvial architecture, color variations on outcrop, and a change in slope (for the full suite of distinguishing characteristics developed across the discontinuity, see Rogers et al., 2016). Fluvial sandstone bodies dominate the alluvial succession below the discontinuity (LAST), with channel/floodplain ratios in sections measured in the McClelland Ferry Member ranging from 0.88 to 2.70 (median 1.13). McClelland Ferry sandstone bodies tend to crop out as distinct, blocky ledges and are often multistory and sheet-like in geometry. Overall, the alluvial strata below the discontinuity weather pale yellow to light gray and hold a somewhat steeper slope punctuated by thick sandstone ledges. In contrast, Coal Ridge strata above the discontinuity (HAST) are dominated by overbank facies, with channel/floodplain ratios ranging from 0.39 to 0.84 (median 0.51). Sandstone bodies above the discontinuity typically weather as rilled slopes, and inclined heterolithic stratification is locally developed. Overall, facies above the mid-Judith discontinuity in the Coal Ridge Member tend to weather to a gray to olive-green appearance, and the outcrop assumes a smoother and often somewhat less steep profile (Fig. 6), although this can vary locally (Rogers et al., 2016). The documented increase in rock accumulation rates and changes in alluvial architecture across the mid-Judith discontinuity are consistent with expectations of the LAST-HAST model outlined above.

The mid-Judith discontinuity is readily identified and mapped in subsurface data sets, where it is marked by an abrupt shift toward the shale baseline in spontaneous potential logs and a coincident decrease in resistivity. The discontinuity is also discernible in gamma-ray logs, where it is marked by a rightward deflection consistent with elevated gamma radiation in the finer-grained strata of the Coal Ridge Member overlying the discontinuity (Rogers et al., 2016). Well logs in the type area of the Judith River Formation indicate that the mid-Judith discontinuity rests, on average, ~90 m above the base of the formation. Well logs throughout the region further suggest that the discontinuity generally occurs 250–265 m above the Eagle/Milk River shoulder.

CA-ID-TIMS GEOCHRONOLOGY

The high-precision U-Pb zircon geochronology and Bayesian stratigraphic-age modeling reported in Ramezani et al. (2022) provide new high-resolution frameworks for several of the dinosaur-bearing units in the Campanian section of the Western Interior Basin, including the Judith River Formation and Belly River Group (Table 1). The new CA-ID-TIMS geochronology significantly improves upon legacy K-Ar and $^{40}Ar/^{39}Ar$ ages from the Judith River–Belly River wedge, and it allows for reassessment of current stratigraphic models and correlations. Independence of the U-Pb ID-TIMS technique from mineral standards with inherent geologic complexities, extensive calibration efforts dedicated to the modern U-Pb CA-ID-TIMS method (e.g., Condon et al., 2015), and its superior precision and demonstrated interlaboratory reproducibility (Schmitz and Kuiper, 2013; Eldrett et al., 2015) make it capable of generating robust ages with internal uncertainties as low as ±12 k.y. in the Campanian (e.g., Ramezani et al., 2022).

Goodwin and Deino (1989) published the first $^{40}Ar/^{39}Ar$ sanidine geochronology from the Judith River Formation, targeting two bentonite beds in Kennedy Coulee in northern Montana (Fig. 1). The new high-precision U-Pb zircon age from this same locality reported in Ramezani

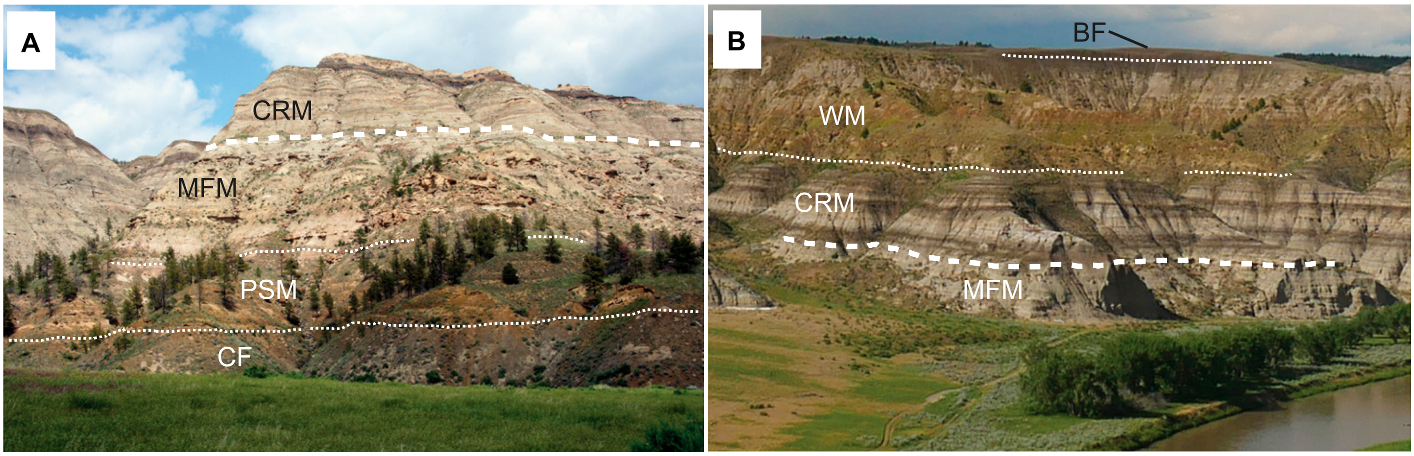


Figure 6. Judith River Formation exposures in the type area in the Upper Missouri River Breaks National Monument. (A) View of mid-Judith discontinuity (thick dashed line) marking contact between McClelland Ferry Member (MFM) and Coal Ridge Member (CRM) at Judith River Formation reference section in vicinity of Stafford–McClelland Ferry (Rogers et al., 2016). Here, an entire section of the Judith River Formation is exposed. Thin dashed lines mark approximate contacts between McClelland Ferry Member, Parkman Sandstone Member (PSM), and Claggett Formation (CF). (B) View of mid-Judith discontinuity (thick dashed line) embedded between McClelland Ferry Member and Coal Ridge Member ~30 km downstream from locality in A. Here, the Coal Ridge Member is capped by shallow-marine sandstones of the Woodhawk Member (WM), which in turn is capped by marine shales of the Bearpaw Formation (BF). Unit contacts are marked by thin dashed lines.

et al. (2022) and referenced here (KC061517-1, Table 1) was derived from a bentonite bed positioned between the two earlier-dated horizons near the top of the "marker A coal" horizon, which is ~10 m above the base of exposure in Kennedy Coulee (Goodwin and Deino, 1989). Subsurface data suggest that the lower portion of the Judith River Formation does not thicken substantially from the type area to Kennedy Coulee, and thus the Kennedy Coulee bentonite KC061517-1 is likely intercalated in strata equivalent to the lignite-rich interval developed in the lower portion of the McClelland Ferry Member in the type area (Rogers et al., 2016). Allowing for the presence of a shallow-marine sandstone body at the base of the formation in Kennedy Coulee comparable in thickness to the Parkman Sandstone Member in the type area, we estimate that the KC061517-1 bentonite is positioned ~25–35 m above the base of the Judith River Formation in Kennedy Coulee.

Rogers et al. (2016) reported three $^{40}Ar/^{39}Ar$ sanidine ages from the Judith River Formation type area in the Upper Missouri River Breaks National Monument in north-central Montana (Fig. 1), targeting two bentonites in the Judith River Formation and one bentonite in the overlying Bearpaw Formation. Two of these previously dated bentonites from the type area were reanalyzed by Ramezani et al. (2022) using the CA-ID-TIMS method (ST1-03 and PPF1-03, Table 1). One new CA-ID-TIMS age from the Dinosaur Park Formation (JC082817-1 bentonite; Ramezani et al., 2022) is also referenced in this report. All ages are presented with 2σ internal uncertainties (Table 1).

REVISED STRATIGRAPHIC FRAMEWORK FOR CAMPANIAN CORRELATION

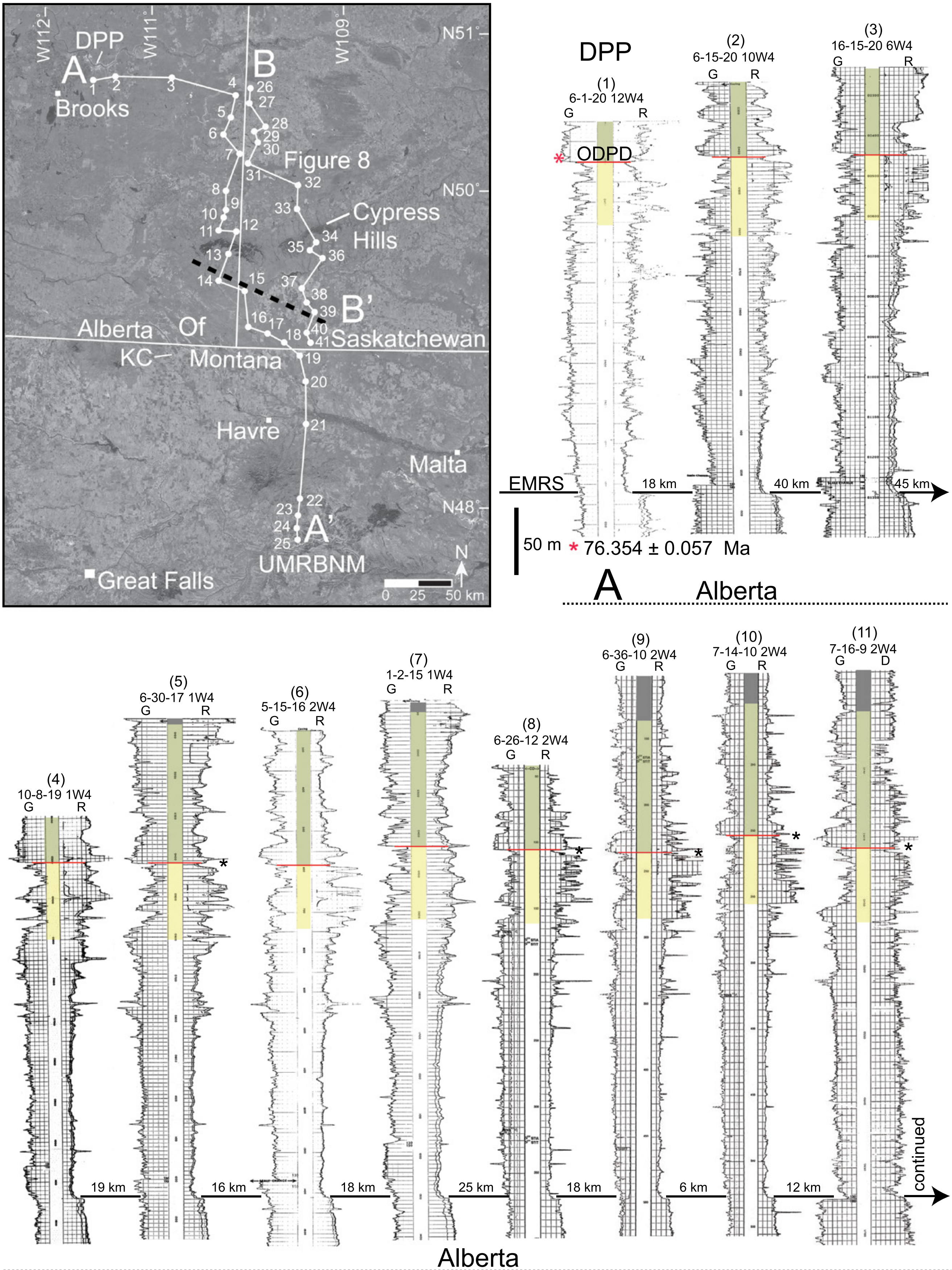
Deciphering the Discontinuities

Determining the relationship and regional expression of the two discontinuities of the Judith River–Belly River wedge was a primary goal of this study, and our comprehensive review of surface and subsurface data suggests two important updates. First, the new U-Pb geochronology from southern Alberta and north-central Montana suggests temporal correlation between the Oldman–Dinosaur Park discontinuity (and formation boundary) in the Dinosaur Provincial Park region and the mid-Judith discontinuity (and member boundary) in Montana. A bentonite bed positioned ~1 m above the Oldman–Dinosaur Park contact in Dinosaur Provincial Park (JC082817-1 bentonite) yielded an age of 76.354 ± 0.057 Ma, and a bentonite bed estimated to be ~4 m below the McClelland Ferry–Coal Ridge contact in the type area of the Judith River Formation (ST1-03 bentonite) yielded an age of 76.329 ± 0.035 Ma (Table 1; Ramezani et al., 2022). The analytical precision on these dates renders the two associated discontinuities essentially indistinguishable with regard to age in these areas. This in turn suggests that the McClelland Ferry Member was deposited concurrently (within the limits of resolution) with the Oldman Formation in Dinosaur Provincial Park, and the Coal Ridge Member accumulated concurrently with the Dinosaur Park Formation in the same region (Rogers et al., 2016).

Ramezani et al. (2022) assessed the ages of the two discontinuities at Dinosaur Provincial Park and in the Judith River Formation type area in north-central Montana using a Bayesian stratigraphic-age model, and their results allowed for up to 300 k.y. (201 ± 99 k.y.) of age variance between the two discontinuities. However, this modeling approach hinges upon the precise placement of discontinuities relative to bracketing bentonites, and this degree of stratigraphic exactitude is not possible given the outcrop expressions of the discontinuities in question. For example, the stratigraphic position of the mid-Judith discontinuity is approximated to within a few meters in outcrop, and the inferred position of the discontinuity illustrated in Judith River reference section 93-JRT-8 in figure 3 of Rogers et al. (2016, p. 104), which was used to inform the model, is an estimate based on the average position of the discontinuity relative to the base of the formation in well logs. Similarly, the composite section of the Belly River Group used to inform the model in relation to the Oldman–Dinosaur Park discontinuity (fig. 4 in Ramezani et al., 2022) was composed of sections measured in different localities, which also adds some degree of uncertainty to the stratigraphy of the bentonites bracketing the discontinuity. Given these limitations and stratigraphic complications that relate to model input, the very precise modeled ages for the two discontinuities may not be geologically meaningful.

A second key update is the realization that the two discontinuities can be readily traced in well logs over a span of ~440 km, from Dinosaur Provincial Park in southeastern Alberta to the Judith River Formation type area in north-central Montana (Fig. 7, section A–A′). The distinctive well-log signature of the Oldman–Dinosaur Park discontinuity can be correlated consistently from Dinosaur Provincial Park to Township 9 (well 7-16-9 2W4), over a span of ~200 km. A change in the nature of the subsurface stratigraphy is evident in the vicinity of the Cypress Hills, an erosional plateau that survived late Wisconsinan glaciation (Kulig, 1996). There, the Oldman–Dinosaur Park discontinuity begins to lose distinction, and the prominent sandstone bodies that delineate the discontinuity so clearly in wells farther to the north thin and become less conspicuous (e.g., wells 6-14-9 1W4 and 6-29-7 1W4, picks of Oldman–Dinosaur Park discontinuity in both from Glombick, 2011b). Subsurface data indicate that the Oldman–Dinosaur Park discontinuity transitions to the mid-Judith discontinuity on the southern flank of the Cypress Hills by Township 5 (e.g., well 10-27-5 2W4), and from there, the mid-Judith discontinuity, with its distinctive well-log signature, can be correlated across Saskatchewan and into north-central Montana, over a span of ~215 km. Importantly, across their expanse and regardless of lithologic expression, the two discontinuities occur at approximately the same stratigraphic height above the Eagle/Milk River shoulder, typically falling ~260 m above this regional marker horizon (Fig. 7). The minor variability in stratigraphic position of the Oldman–Dinosaur Park discontinuity above the Eagle/Milk River shoulder in section A–A′ can be ascribed to "local erosional topography" on the basal surfaces of large paleochannels clustered at the base of the Dinosaur Park Formation, which Eberth and Hamblin (1993, p. 185) estimated to be up to 30 m. Some of this variability may also reflect minor stratigraphic irregularity of the datum itself, which is certainly a possibility given the expanse of the discontinuity and datum in section A–A′, and the vagaries of compaction. In any case, there is no indication in well logs of a directional (southward) multi-decameter (50 + m) climb of the Oldman–Dinosaur Park discontinuity between Dinosaur Provincial Park and the Alberta-Montana border region.

Similar subsurface stratigraphy is evident in southwestern Saskatchewan (Fig. 8, section B–B′), where the Oldman–Dinosaur Park discontinuity can be traced continuously from Township 19 (well 6-33-19 29W3) to Township 3 (well 14-36-3 25W3), a span of ~180 km. As in Alberta, the discontinuity loses distinction to the south and transitions to the mid-Judith discontinuity, which is evident in well 8-7-2 25W3 in Township 2. The mid-Judith discontinuity can be traced from this point south across the international border to the Judith River Formation type area in north-central Montana, a span of ~150 km. These subsurface data from southwestern Saskatchewan suggest that the thick sandstone bodies that mark the Oldman–Dinosaur Park discontinuity track southeastward from the Cypress Hills region in Alberta (section A–A′, Township 9) to the border region of southern Saskatchewan (section B–B′, Township 3). This trend, delineated by the dashed black line on the map in Figure 7, suggests that the ancient fluvial system represented by the thick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(6)
5-15-16 2W4
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(7)
1-2-15 1W4
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(8)
6-26-12 2W4
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(9)
6-36-10 2W4
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7-14-10 2W4
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Alberta

Figure 7. Subsurface expression of the Oldman–Dinosaur Park discontinuity (ODPD) and mid-Judith discontinuity (MJD) from the vicinity of Dinosaur Provincial Park (DPP) in southeastern Alberta to the Upper Missouri River Breaks National Monument (UMRBNM) in north-central Montana (path of subsurface section A–A′ indicated on map, wells 1–25). See text for descriptions of subsurface signatures that identify each discontinuity across the region. The red line in each log indicates the inferred position of each discontinuity (solid for Oldman–Dinosaur Park discontinuity, dashed for mid-Judith discontinuity). Both discontinuities maintain a relatively consistent stratigraphic position in relation to the Eagle/Milk River shoulder (EMRS), a widely recognized marker horizon (e.g., Glombick and Mumpy, 2014). Picks of Foremost-Oldman, Oldman–Dinosaur Park, and Dinosaur Park–Bearpaw contacts are informed by Glombick (2010a, 2010b, 2011a, 2011b, 2013). Picks of the Oldman–Dinosaur Park discontinuity that coincide with picks made by Glombick (2011b) in the same logs are indicated by black asterisks. Black dashed line on map indicates where Oldman–Dinosaur Park discontinuity to the north shifts to mid-Judith discontinuity to the south. Yellow—Oldman Formation; light green—Dinosaur Park Formation; light brown—Coal Ridge Member of Judith River Formation; darker brown—McClelland Ferry and Parkman Sandstone Members of Judith River Formation; dark gray—Bearpaw Formation. Judith River reference section 91-JRT-8 is from Rogers et al. (2016). KC—Kennedy Coulee field area; Of—Onefour field area; CF—Claggett Formation; BF—Bearpaw Formation; G—gamma-ray log; D—density log; R—resistivity log; S—sonic log; SP—spontaneous potential log.

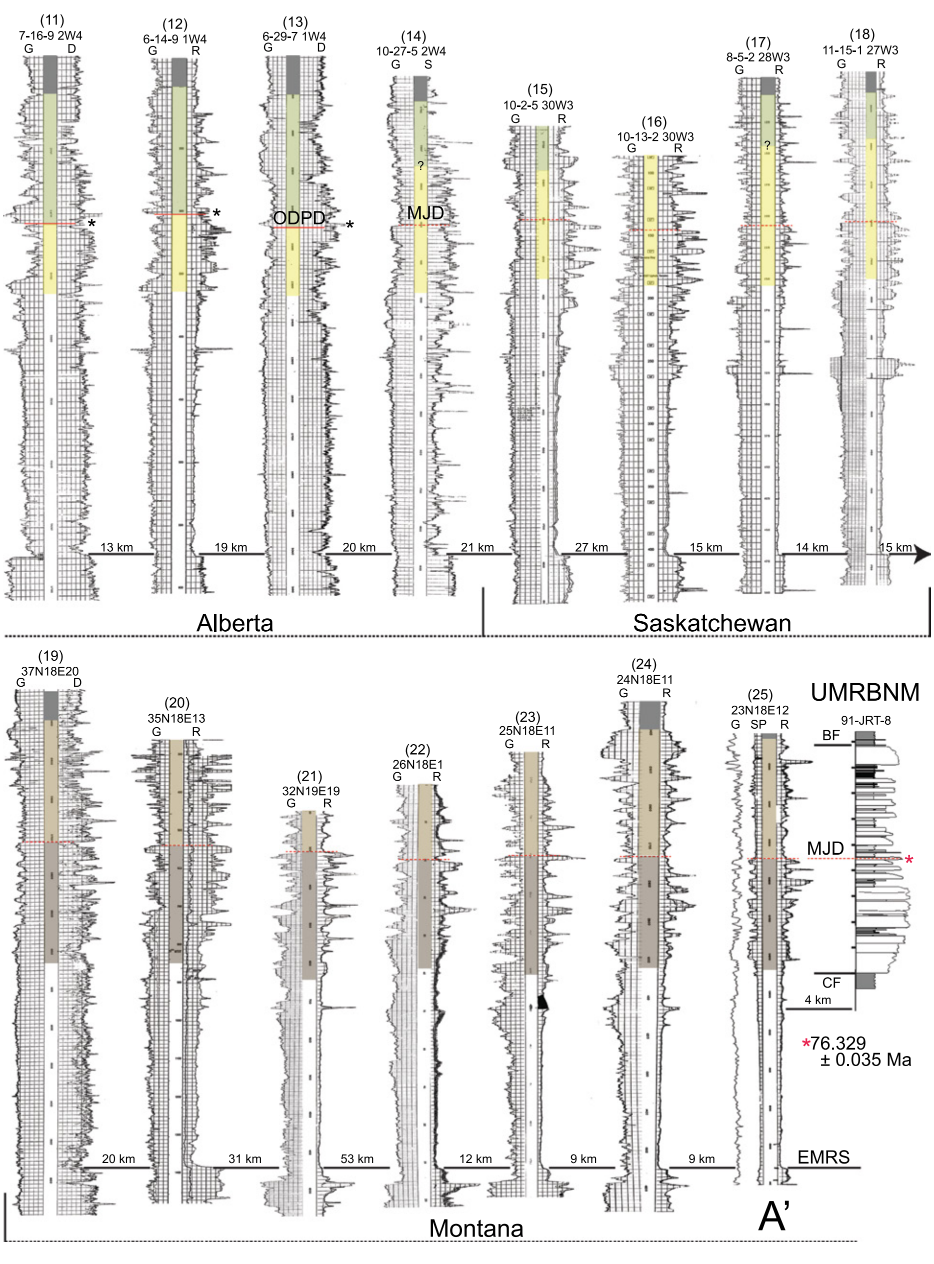

Figure 7. (*Continued*)

multistory paleochannel deposits clustered at the base of the Dinosaur Park Formation trended in a southeasterly direction, a reconstruction previously advanced by Eberth and Hamblin (1993) based on paleocurrent data. Again, in section B–B′, the two discontinuities occur at approximately the same stratigraphic height (~258 m) above the Eagle/Milk River shoulder, and there is no indication of a southward climb of the Oldman–Dinosaur Park discontinuity (Fig. 8).

These findings have important implications for regional correlation and the geological history of the Judith River–Belly River wedge. First and foremost, with regard to correlation, the two discontinuities represent a pair of readily discernible stratigraphic markers that can be used to correlate from Dinosaur Provincial Park in southeastern Alberta to the type area of the Judith River Formation in north-central Montana. In Montana and Alberta, the discontinuities are delineated in outcrop by shifts in lithology significant enough to clearly demarcate formal unit boundaries (McClelland Ferry and Coal Ridge Members in Montana, Oldman and Dinosaur Park Formations in Alberta). Likewise, they are readily identified and correlated in well logs extending from north-central Montana through southwestern Saskatchewan and southeastern Alberta up to the environs of Dinosaur Provincial Park (Figs. 7 and 8) and beyond (Macdonald et al., 1987).

With regard to geological history and the integration of tectonics and sedimentation at the basin scale, it is herein again argued that the mid-Judith discontinuity represents a tectonically linked expansion surface that marks a regional reorganization of depositional systems in response to a major pulse of accommodation in the basin (Rogers, 1998; Rogers et al., 2016). Rock accumulation rates in the Judith River Formation are consistent with an increased rate of addition of accommodation across the discontinuity, with a more than threefold increase above the discontinuity in the Coal Ridge Member

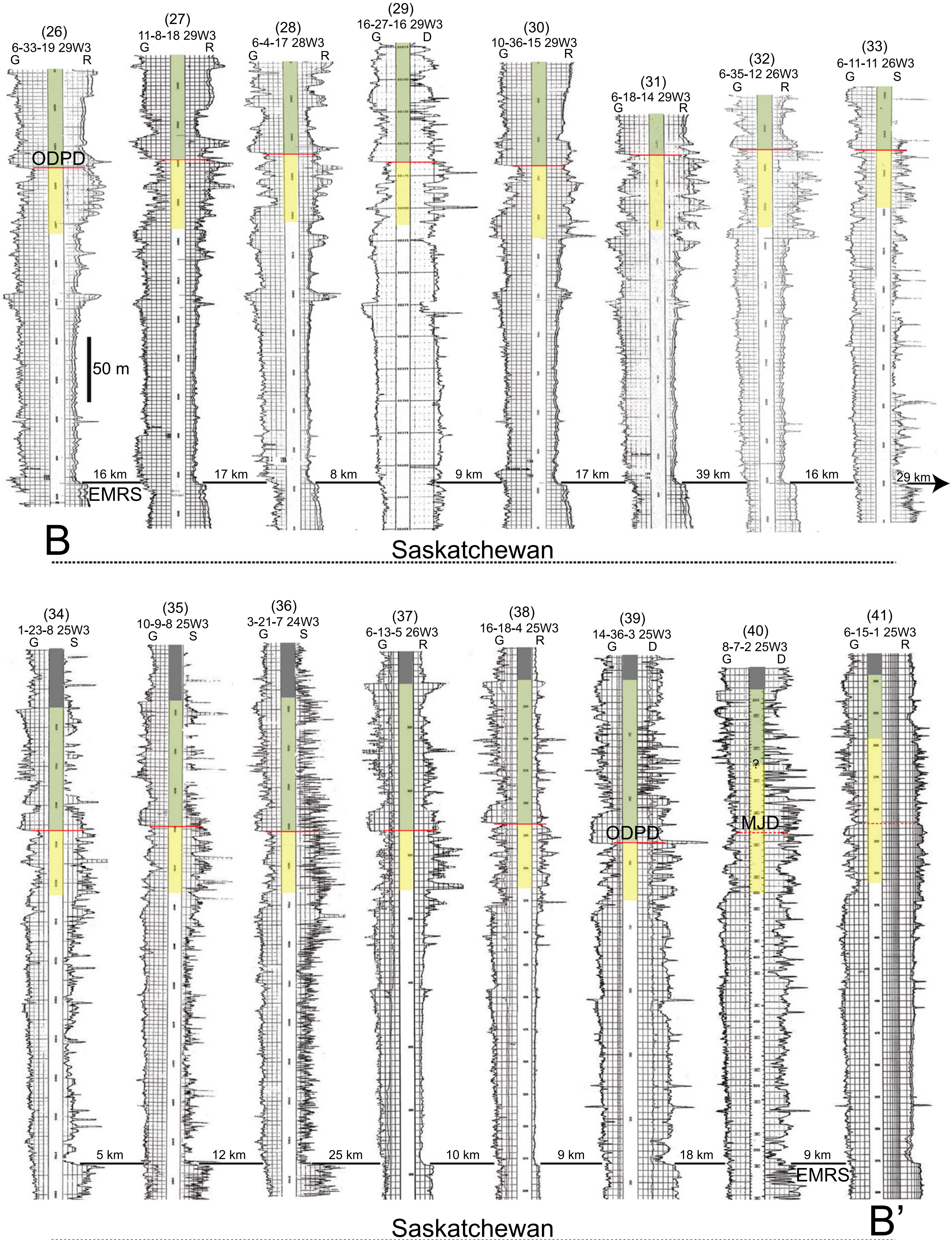
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Figure 8. Subsurface expressions of the Oldman–Dinosaur Park (ODPD) and mid-Judith (MJD) discontinuities in southwestern Saskatchewan from Township 19 (along the Saskatchewan-Alberta border) to Township 2 in southernmost Saskatchewan (see Fig. 7 for path of B–B′ subsurface section, wells 26–41). The red line in each log indicates the inferred position of each discontinuity (solid for Oldman–Dinosaur Park discontinuity, dashed for mid-Judith discontinuity). As in Alberta, the Oldman–Dinosaur Park discontinuity and mid-Judith discontinuity maintain a relatively consistent stratigraphic position in relation to the Eagle/Milk River shoulder (EMRS). Picks of Foremost-Oldman, Oldman–Dinosaur Park, and Dinosaur Park–Bearpaw contacts follow criteria used by Glombick (2010a, 2010b, 2011a, 2011b, 2013) for nearby portions of Alberta. Yellow—Oldman Formation; light green—Dinosaur Park Formation; dark gray—Bearpaw Formation; G—gamma-ray log; D—density log; R—resistivity log; S—sonic log.

(see above). This reconstruction now effectively translates to the strata north of the international border, where the mid-Judith discontinuity can be shown to correlate with the Oldman–Dinosaur Park discontinuity. The U-Pb geochronology of Ramezani et al. (2022) indicates that the rock accumulation rates across the Oldman–Dinosaur Park discontinuity rose from ~1.9 cm/k.y. in the Oldman Formation to ~4.0 cm/k.y. in the Dinosaur Park Formation. The geochronology of the Dinosaur Park Formation also suggests that rates declined up section through the unit to the base of the marine Bearpaw Formation (Eberth et al., 2023).

From a depositional systems standpoint, the implication is that the pulse of added accommodation at ca. 76.3 Ma had impacts more widespread than originally envisioned, and the response was complex from a facies perspective and potentially synchronous, or nearly so (within limits of resolution), across a sizeable paleogeographic expanse. Strata of the Judith River Formation in north-central Montana change dramatically across the mid-Judith discontinuity, as evidenced by a marked shift in alluvial architecture. The alluvial record essentially "muddies-up," with fine-grained floodplain deposits dominating the alluvial succession above the discontinuity. In the contemporaneous marine realm, deposition of the Woodhawk Member marks the onset of the Bearpaw transgression, which commenced at ca. 76.3 Ma (Rogers et al., 2016; Ramezani et al., 2022). The onset of transgression presumably correlates with the same accommodation event. Farther to the north, in the plains of southern Alberta and Saskatchewan, the initial pulse of added accommodation coincides, again within the limits of resolution, with the establishment of a large southeast-trending network of stacked paleochannels. Deposits of these outsized paleochannels, which pass laterally and conformably to contemporaneous floodplain facies above the mid-Judith discontinuity in southernmost Alberta and Saskatchewan, and Montana (Figs. 7 and 8), define the base of the Dinosaur Park Formation and delimit the Oldman–Dinosaur Park discontinuity in the Dinosaur Provincial Park region and beyond (Eberth and Hamblin, 1993). Distinctive deposits of these ancient multistory channels also host one of the richest records of dinosaur fossils on Earth (Currie and Koppelhus, 2005).

Last, we propose that the term "Judith River–Belly River discontinuity" be used henceforth to refer to the regionally expressed stratal discontinuity that subdivides the Judith River–Belly River wedge. We recognize that the discontinuity changes in expression across its expanse, but applying a single term is deemed appropriate because the discontinuities in question (Oldman–Dinosaur Park discontinuity and mid-Judith discontinuity) reflect a single causal event (an abrupt increase in the rate of addition of accommodation) that transpired at the same time (ca. 76.3 Ma) throughout the Montana-Alberta-Saskatchewan portion of the Western Interior Basin. This update to the terminology effectively unites reconstructions developed on opposite sides of the international border and is unencumbered by and uncoupled from more localized terminologies.

Lithostratigraphic Considerations

The stratigraphic model outlined above provides an updated framework for contextualizing the lithostratigraphy of the Judith River–Belly River wedge in relation to the Judith River–Belly River discontinuity (Fig. 9). Data indicate that the McClelland Ferry Member, which represents the terrestrial record in the lower half of the Judith River Formation, is the lithological equivalent of the Oldman Formation. There is no question that the two units are comparable, and arguably indistinguishable, in outcrop. Both are characteristically light gray to pale yellow/tan, with generally steep and sometimes blocky exposure, and both are relatively enriched in quartz and kaolinite (Eberth and Hamblin, 1993; Rogers et al., 2016). Moreover, both the McClelland Ferry Member and the Oldman Formation are characterized by fewer well-preserved vertebrate fossils overall (but see Regan et al., 2022), and far fewer discrete bentonites than overlying strata (Coal Ridge and Dinosaur Park). Importantly, Eberth and Hamblin (1993, p. 194) have already concluded that Judith River Formation exposures in north-central Montana, with the exception of some localized outcrops near Havre along the Milk River and potentially the uppermost few meters in the type area, are "lithostratigraphically identical" to the Oldman Formation in Alberta.

Deciphering the relationship between the Coal Ridge Member of the Judith River Formation and the Dinosaur Park Formation is a somewhat more complicated endeavor. Rogers et al. (2016) described many distinguishing features of the Coal Ridge Member relative to the underlying McClelland Ferry Member, including (1) darker gray to olive-green color in outcrop, (2) smooth-weathering slopes, (3) abundant brown to black carbonaceous beds, including numerous lignites, (4) abundant bentonite beds, (5) relative enrichment in volcanic rock fragments, plagioclase, and smectite matrix, (6) abundant vertebrate fossils, including plentiful vertebrate microfossil bonebeds (Rogers and Brady, 2010; Rogers et al., 2017), and (7) localized lags of extraformational clasts (predominantly black and gray chert, quartzite, quartz, and bedded metasedimentary pebbles) in sandstone bodies located near the base of the member. These same features also characterize the Dinosaur Park Formation, and they are generally inconsistent with published characterizations of the Oldman Formation (Eberth and Hamblin, 1993; Hamblin, 1994, 1997; Eberth, 2005).

One very distinctive facies that typifies the Dinosaur Park Formation within Dinosaur Provincial Park is notably rare in the Coal Ridge Member within Montana. Thick multistory sandstone bodies that exhibit large-scale inclined heterolithic stratification are common in the lower half of the Dinosaur Park Formation, and it is in fact these ancient paleochannel deposits, coupled with the underlying "upper siltstone member" of the Oldman Formation (see above), that drive the distinctive subsurface signature at the base of the unit in Alberta and Saskatchewan (Figs. 7 and 8): the strong leftward deflection in gamma-ray log response that marks the Oldman–Dinosaur Park discontinuity coincides with the base of prominent sandstone bodies (Eberth and Hamblin, 1993; Glombick, 2011a, 2011b). Sandstone bodies characterized by inclined heterolithic stratification are also present in the Coal Ridge Member both within the formation type area and in the vicinity of Havre, where the Coal Ridge Member crops out widely in the bad-

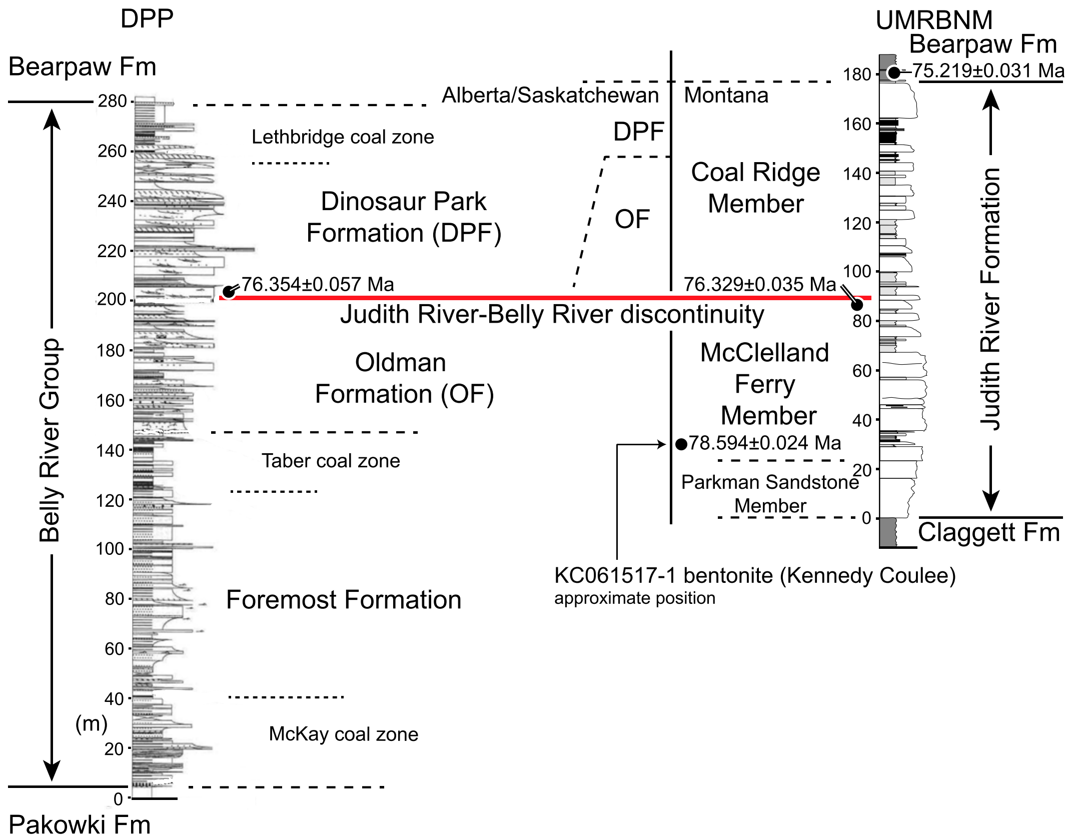

Figure 9. Formal and informal lithostratigraphic units in Judith River–Belly River wedge. The ~280-m-thick Belly River section in the vicinity of Dinosaur Provincial Park (DPP), Alberta, is a composite log based on surface and subsurface data sets (modified from Eberth and Hamblin, 1993), and here the Judith River–Belly River discontinuity, dated to ca. 76.354 ± 0.057 Ma, separates the Oldman and Dinosaur Park Formations. The ~180-m-thick Judith River section in the Upper Missouri River Breaks National Monument (UMRBNM) in Montana is a surface section that includes lower and upper contacts with the Claggett and Bearpaw Formations, respectively (modified from Rogers et al., 2016). Here, the Judith River–Belly River discontinuity, dated to ca. 76.329 ± 0.035 Ma, separates the McClelland Ferry and Coal Ridge Members of the Judith River Formation. A bentonite dated to 75.219 ± 0.031 Ma rests ~90 m above the discontinuity, near the base of the Bearpaw Formation. Another bentonite dated to 78.594 ± 0.024 Ma occurs near the base of the Judith River Formation in the "marker A coal" bed identified by Goodwin and Deino (1989) in the Kennedy Coulee field area. The discontinuity can be tracked from north-central Montana into Alberta and Saskatchewan at the same general stratigraphic position above the Eagle/Milk River shoulder (see text for discussion). The basal contact of the Dinosaur Park Formation diverges from the Judith River–Belly River discontinuity in southernmost Alberta and Saskatchewan and climbs stratigraphically to the south toward the international boundary, as previously described in Eberth and Hamblin (1993) and Eberth (2005).

lands along the Milk River, but they tend to be thinner and more localized than their Dinosaur Park Formation counterparts, and they are not clustered at the base of the unit (Rogers, 1998; Rogers et al., 2016).

In previous reconstructions that posited a strongly diachronous nature for the Oldman–Dinosaur Park discontinuity in the plains of southern Canada (e.g., Eberth and Hamblin, 1993; Eberth, 2005), this transition was interpreted to mark the intersection of the aforementioned Dinosaur Park and Oldman megafan lobes (Fig. 4), with the Oldman–Dinosaur Park discontinuity rising stratigraphically to the southeast over many tens of meters (estimates range up to 50 m) between Dinosaur Provincial Park and the Alberta-Montana border region. In this earlier reconstruction, the Oldman and Dinosaur Park lobes were interpreted to have accumulated discretely and concurrently on opposite sides of the diachronous discontinuity, with up to 1.5 m.y. of temporal overlap (Eberth and Hamblin, 1993). Data presented in this report are inconsistent with this interpretation as it relates to the nature of the Judith River–Belly River discontinuity, and they suggest instead that the discontinuity is far less diachronous than previously surmised.

However, there is still indication that the contact between the Oldman Formation and the overlying Dinosaur Park Formation is diachronous. This lithostratigraphic boundary, which is generally delimited at the base of large sandstone bodies in the subsurface and at the surface (Eberth and Hamblin, 1993), decouples and diverges from the underlying discontinuity to the south of the Cypress Hills in southeastern Alberta and in Township 2 in southwestern Saskatchewan (Figs. 7 and 8). From these points south, the contact between the Oldman Formation and Dinosaur Park Formation can be difficult to pick with certitude in well logs using the criteria of Eberth and Hamblin (1993) and Glombick (2011a), but surface sections in the Onefour and Manyberries area of southern Alberta suggest that the base of the Dinosaur Park Formation is ~30 m beneath the contact with the overlying Bearpaw Formation (Eberth and Hamblin, 1993; Eberth, 2005). In this region, and in southernmost Saskatchewan, strata representing the upper Oldman Formation are intercalated between the base of the overlying Dinosaur Park Formation and the underlying Judith River–Belly River discontinuity (Figs. 7–9).

SUMMARY AND CONCLUSION

In this report, we evaluated current notions of Campanian stratigraphy represented in the Judith River–Belly River wedge in the context of a high-resolution age model based on U-Pb zircon geochronology (Ramezani et al., 2022). New geochronology indicates that the Oldman–Dinosaur Park discontinuity in Dinosaur Provincial Park correlates in age with the mid-Judith discontinuity in the Judith River Formation in

Montana. The two discontinuities are equivalent in age (within the limits of resolution), and this realization clarifies the age relations of stratigraphic units that bound the discontinuities in these two field areas. In addition, the mid-Judith discontinuity and the Oldman–Dinosaur Park discontinuity can be correlated in well logs over a span of at least 440 km, from the Judith River Formation type area in north-central Montana to Dinosaur Provincial Park in southeastern Alberta. Over this expanse, the two discontinuities occur at approximately the same stratigraphic height above the Eagle/Milk River shoulder, and together they represent time-significant lithologic markers that can be used to correlate strata throughout the region, from north-central Montana into the plains of southern Canada (Figs. 7 and 8). This realization has important implications for future studies of a geological nature in the Judith River–Belly River wedge, which can now proceed in an updated chronostratigraphic framework. Exploration of the amazing fossil resources of the study interval can also now be advanced in an updated stratigraphic framework calibrated with high-precision U-Pb zircon geochronology directly associated with the time-significant "Judith River–Belly River discontinuity," a new term that is herein proposed in lieu of the "Oldman–Dinosaur Park" and "mid-Judith" discontinuities.

These findings also have important implications for applications of terrestrial sequence stratigraphy, because the pulse of added accommodation that is interpreted to have coincided with formation of the Judith River–Belly River discontinuity and onset of the Bearpaw transgression in north-central Montana (Rogers, 1998; Rogers et al., 2016) can now be shown to correlate closely in time with the establishment of a major fluvial drainage network throughout significant portions of southern Alberta and southwestern Saskatchewan. The complex regional shifts in alluvial architecture that delimit the Judith River–Belly River discontinuity and mark unit boundaries were apparently synchronous, or very nearly so, across the region and were almost certainly allogenic in origin and linked to the tectonic evolution of the basin. Future work will focus on tracking the accommodation-related discontinuity beyond the current study area (e.g., Macdonald et al., 1987) and documenting the complex and variable response of the Judith River–Belly River alluvial system to this widespread episode of added accommodation.

Finally, the revised stratigraphic model for the Judith River–Belly River wedge described herein affords an impetus and opportunity to evaluate existing interpretations and further refine our understanding of these classic Campanian strata and fossils. Moving forward, some existing correlations and related paleobiological reconstructions may need to be reassessed and perhaps adjusted. The result will be a more accurate understanding of Campanian history for the region and a more refined calibration and appreciation of the dinosaur fossil record.

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