The Bakken Formation – understanding the sequence stratigraphic record of low-gradient sedimentary systems, shale depositional environments, and sea-level changes in an icehouse world

Sven O. Egenhoff and Neil S. Fishman

ABSTRACT

The Bakken Formation is a major petroleum producer in the continental US. However, its deposition in an intracratonic, low-gradient setting has often been mistakenly described as "layer-cake". This contribution is designed to highlight the time-transgressive nature of its main petroleum-producer, the middle Bakken member. Correlation of individual parasequences reveal the subtle nature of otherwise invisible low-angle stratigraphic geometries. Sequence stratigraphically-relevant surfaces occur throughout the unit and subdivide the entire Bakken into 5 third-order sequences; one of them is a hidden sequence at the base of the petroleum-producing middle Bakken indicating both a lowstand and a subsequent transgression. The organic-rich shales above and below the middle Bakken were deposited in an oxygen-deficient environment and show several burrow/fecal string types and indications of active currents during deposition. The Bakken records high amplitude sea-level changes during sequences compared to relative low amplitude sea-level changes of parasequences. This, coupled with a likely mismatch in timing of Bakken deposition relative to world-wide ice-age-induced cyclicity makes it unlikely that the Bakken sea-level fluctuations were dominated by glaciation.

INTRODUCTION

The Upper Devonian-Lower Mississippian Bakken Formation is a focus of interest in parts of North Dakota and Montana because of its world-class source rocks and petroleum production (e.g., Gaswirth et al. 2013). Despite the keen interest in it, the internal stratigraphic geometries of the Bakken are so subtle that many consider the formation as a perfect example of layer-cake stratification (e.g. Meissner 1978; Sonnenberg and Pramudito 2009; Hart and Hofmann 2020). However, the sedimentary architecture of the Bakken, like other units deposited in intracratonic basins, is characterized by geometries that are at very low inclination—sub-parallel to the basin floor—making it difficult to recognize them in core or on well-logs. This contribution aims to clarify the subtlety of an intracratonic basin fill during sea-level fluctuations using the Bakken as an example. In this context, characterizing the sequence stratigraphy of the Bakken, as well as the depositional environment of all members of the formation, are of crucial importance. They allow us to reconstruct the dynamics of this sedimentary system and the relationship between the two organic-rich siliciclastic shales that overlie and underlie the middle member—a carbonate-siliciclastic unit. Ultimately, this understanding enables prediction of the characteristics of all these units. Lastly, the sea-level changes recorded in the Bakken are evaluated in the context of possible glacioeustasy related to an icehouse world.

GEOLOGICAL SETTING

The Williston Basin, an intracratonic trough formed in the Cambrian (Gerhard et al. 1990), occupies portions of present-day United States and Canada (e.g. Borcovsky et al. 2017; Fig. 1). The Bakken Formation component of the sedimentary succession is especially important because its two organic-rich shales were the source of petroleum in much of the Paleozoic section, including the overlying Mississippian Madison Group (Chen et al. 2009) and the underlying Three Forks Formation (e.g., Gaswirth et al. 2013). During Bakken deposition, the Williston Basin was subequatorial (Scotese 1994). The Bakken is up to 45 m thick (Meissner 1978), and is exclusively in the subsurface.

THE SEQUENCE STRATIGRAPHY OF LOW-ANGLE DEPOSITIONAL SYSTEMS – THE BAKKEN AS A PRIME EXAMPLE

The Bakken Formation is comprised of four informal members (LeFever et al. 2011; Fig. 1): the basal Sanish/Pronghorn member (SP), which is aerially restricted, consists of sandstones and siltstones and locally a carbonate. Where present, it has a sharp contact with the underlying Three Forks Formation (Fig. 1; e.g. LeFever et al. 2011). The SP is overlain with a sharp contact by the lower Bakken shale (LBS), a black shale containing clay, organic

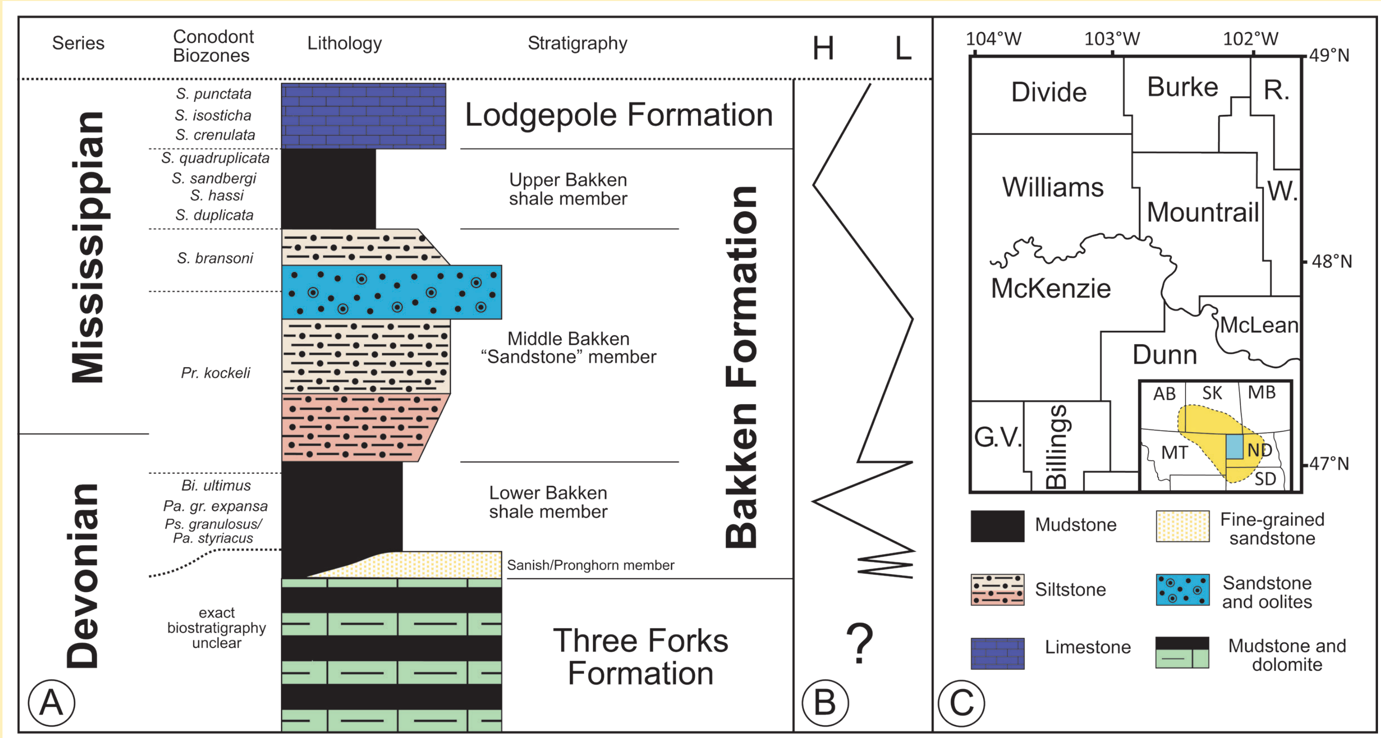

Figure 1: Stratigraphy of the Bakken Formation in North Dakota and Montana (A), a schematic reconstruction of sea-level evolution during Bakken times (B), and a location map of study area (blue, right side of figure) within the Williston Basin (yellow; C). Abbreviations of fossil names: Bi. = Bispatodus; *Pa.* = Palmatolepsis; *Pr.* = Protognathus; *Ps.* = Pseudopolygnathus; *S.* = Siphonodella *(fossil identification after Hogancamp and Pocknall, 2018); H= high sea-level, L= low sea-level.*

matter, quartz silt, carbonate silt, and radiolarian microfossils. The LBS is organized into two sub-units; the lower half demonstrates an overall grain size decrease stratigraphically upwards, whereas the upper half contains more abundant siltstone beds as compared to the lower half (Albert 2014). The boundary between the LBS and the overlying middle Bakken (MB) is commonly sharp, with a centimeter-thick carbonate unit and clastic dikes tapering downward from the MB into the LBS (Egenhoff 2017). The MB consists dominantly of siliciclastics and subordinate carbonates, and is organized into two broad sub-units; the lower sub-unit (representing 1/2 to 3/4 of the succession) exhibits a generally coarsening-upward character, whereas the upper sub-unit broadly demonstrates a fining-upward character (Fig. 2; Novak and Egenhoff 2019). The lower sub-unit contains decimeter- to several meter-scale coarsening-upward packages that increase in number from the margin of the basin into the center (Egenhoff et al. 2011). The overlying upper Bakken shale (UBS) can be subdivided into 2 sub-units; the lower sub-unit contains abundant detrital clay, quartz, radiolaria, and organic-matter. In contrast, the upper sub-unit contains less quartz, fewer radiolaria, less organic matter but more clay than the lower sub-unit (Borcovsky et al. 2017).

Interpretation

The SP member is interpreted to have two regressive episodes — the siliciclastics – with an intervening transgressive episode – the carbonate. The sharp contact with the LBS shows a well-developed transgressive surface (Smith and Bustin 2000; Egenhoff et al. 2011) culminating in a highstand that corresponds to the top of the lower subunit of the LBS (Albert 2014). A regression separating the LBS from the MB is recorded by the upward coarsening in the upper subunit of the LBS along with the siliciclastic infill of the clastic dikes. This regression was followed by a transgression represented by the carbonates (Egenhoff 2017). The lower part of the MB contains 1-6 parasequences (in fig. 2 up to 5 are shown but 6 are present in well Ansbro Petroleum Loucks 44-30; Novak et al. submitted) interpreted as a forced regression and basinward progradation capped by a maximum regressive surface. The basinward progradation lead to successive exposure of the basin margins and resulted in a varying number but overall fewer parasequences at the margins versus the basin center. Following this regression <4 poorly organized parasequences record the subsequent transgression (Novak and Egenhoff 2019; Novak et al. submitted). Within the UBS, a lower transgressive section (the lower subunit) is overlain by an upper regressive section (Borcovsky et al. 2017).

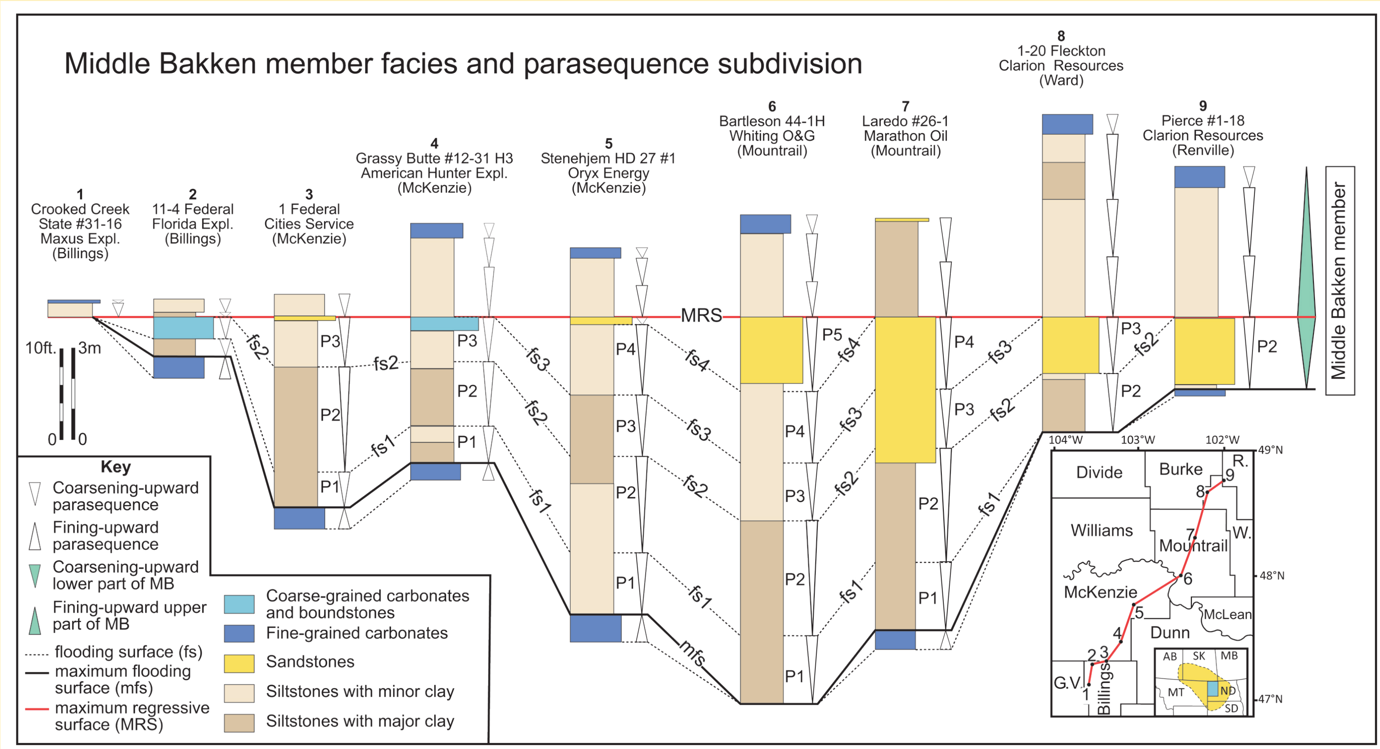

Figure 2: Stratigraphic cross-section through western ND from SW to NE simplified from Novak et al. submitted; note how the middle Bakken (MB) increases in thickness and shows more parasequences in the center of the basin (section 6) than towards the margins where it pinches out (section 1) or is reduced to a single parasequence (section 9). Lithological details are provided in Novak et al. submitted.

Therefore, the sequence stratigraphic framework of the Bakken Formation demonstrates at least 5 third-order sequences.

SUBTLE SEDIMENT GEOMETRIES INVOLVING THE UPPER BAKKEN SHALE

The UBS demonstrates a successively increasing number of parasequences from basin margin to center. Up to 22 decimeter to meter-scale coarsening- and fining-upward parasequences are observed in the basin center, whereas only 8-11 parasequences have been observed in cores close to the margin (Fig. 3; Borcovsky et al. 2017). The lower part of the UBS largely retains its thickness through the basin while the upper part thins from center to margin. Fecal strings and burrows are present throughout the UBS but decrease in abundance basinward from the margins. The same holds true for burrowing intensity, scours, and siltstone laminae (Borcovsky et al. 2017).

<u>Interpretation</u>

The overall basinward increase in the number of parasequences coupled with the decrease in thickness of the upper UBS is interpreted as reflecting an interfingering between the UBS and overlying carbonates of the Lodgepole Formation. Fecal strings and burrows in the UBS indicate at least oxygen-depleted conditions during deposition, and energy indicators such as ripple foresets and siltstone laminae show the influence of bed load on deposition (Fig. 3) particularly in more proximal reaches. The overall basinward decrease in these energy indicators implies currents, likely induced by storms (Egenhoff and Fishman 2013), which had a decreasing influence on bed load processes from the margin to the basin center.

SEA-LEVEL CHANGES IN AN ICEHOUSE WORLD

The Bakken Formation is broadly bounded by two well-documented, worldwide ice ages: the Late Devonian “Kellwasserkalk event” (Buggisch 1991) and the Carboniferous-Permian event best represented by Pennsylvanian cyclothems (Heckel 1986). Nevertheless, the later event likely started to leave a significant mark in the rock record in the Viséan (Early Carboniferous, e.g., Fielding and Frank 2015). Thus, neither of these recognized icehouse events are time equivalent to Bakken deposition (Fig. 4). Also, the Bakken shows distinct sea-level changes, prominently of two orders. Those that were longer, herein considered sequences, are likely about a million or more years in duration (e.g. Hogancamp and Pocknall 2018), whereas the shorter ones, equivalent to parasequences, were several tens to hundreds of thousands

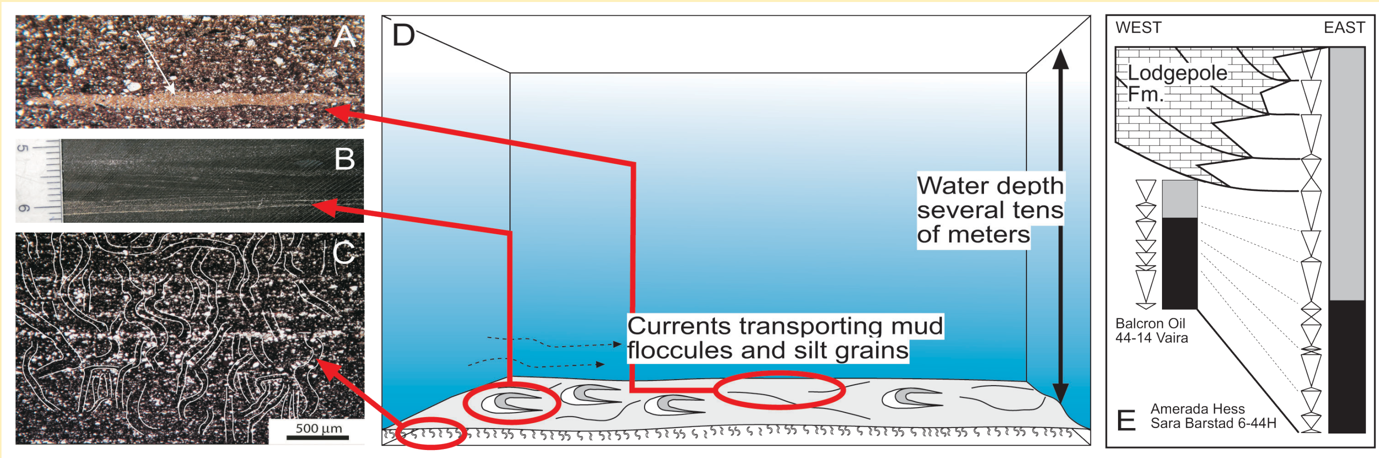

Figure 3: Depositional setting as envisioned for the LBS and UBS – (A) Planolites isp. (white arrow) is present in many of the thin sections, horizontal length is 700μm; (B) current ripples occur relatively frequently throughout the succession but are rarely well preserved, scale is in millimeters (modified from Egenhoff and Fishman 2013); (C) Phycosiphon incertum type B is observed in every thin section in great abundance (modified from Egenhoff and Fishman 2013); (D) envisioned conditions on the sea floor during deposition with migrating ripples, burrows, and fecal strings; (E) envisioned lateral transition between UBS in the Balcron Oil Vaira well close to the margin, and in the Amerada Hess Sara Barstad well representing the basin center; note the equivalency of the carbonates of the overlying Lodgepole Formation with the upper part of the UBS; upwards opening triangles – coarsening-upward, upward closing triangles – fining-upward; black represents lower portion of UBS, grey represents upper part of UBS, tiles represent Lodgepole carbonates; data from Borcovsky et al. (2017).

of years in duration (Novak et al. submitted). Importantly, the amplitude of the Bakken sequences is higher than the amplitude of the parasequences (see data in Egenhoff et al. 2011 and Novak et al. submitted). The relationship of sequences to parasequence in the Bakken would be atypical for sea-level fluctuations during a global ice-age where parasequences formed by Milankovitch-type cyclicity show very large amplitudes generally overshadowing everything else (e.g. Heckel 1986). As such, it seems unlikely that prominent ice-age derived sea-level fluctuations are recorded in the Bakken sequences or parasequences. Accordingly, we do not subscribe to the assignment of glacially-influenced cycles governing Bakken deposition as suggested by Hart and Hoffman (2020).

A similar picture emerges when data from the Bakken are compared to time-equivalent strata worldwide. The onset of ice-age type cyclicity is thought to have occurred in the upper Viséan according to successions in Scotland (Fielding and Frank 2015) which is post Bakken deposition; a similar age (Viséan to Serpukhovian) is reported from continental deposits sitting on striated bedrocks in the Paraná Basin of Brazil (Rosa et al. 2019). Glacial deposits in a fjord system in Argentina (Alonso-Muruaga et al. 2018) also point to a Viséan age for the onset of glacial deposition. Nevertheless, Lakin et al. (2016) were able to pinpoint three glaciation spikes in the latest Famennian, the mid-Tournaisian, and the Viséan in distinct regions of South America, Appalachia, and Africa before the onset of the main Carboniferous-Permian glaciation reported elsewhere. It therefore seems very probable that the Late Devonian glaciation is a direct precursor of the Carboniferous and Permian ice age; nevertheless, this ice age is not seen worldwide in cyclic sediments before the Viséan (see above).

DISCUSSION

A sequence stratigraphic interpretation of the Bakken Formation has been offered several times. Smith and Bustin (2000) presented an initial and controversial model; two of its shortcomings were that it largely equates the Bakken members with individual systems tracts, and its age correlations are not widely accepted. Another model (Hart and Hofmann 2020) relies heavily on glaciation as the driver of sea level change, although we argue there is a paucity of evidence of glaciation influencing Bakken deposition (see above). Instead, detailed sedimentological studies (e.g., Borcovsky et al. 2017; Egenhoff 2017) along with a comprehensive ichnological study (Angulo and Buatois 2012), as well as stratigraphic studies (LeFever et al. 2011) make clear that there is much more complexity in the entire Bakken succession than that proposed by Smith and Bustin (2000) or Hart and Hofmann (2020). Indeed, a properly developed sequence stratigraphic model for the Bakken succession requires inclusion of the entire package of rocks, from the SP through the UBS (Fig. 1).

Perhaps most important in interpreting the Bakken succession

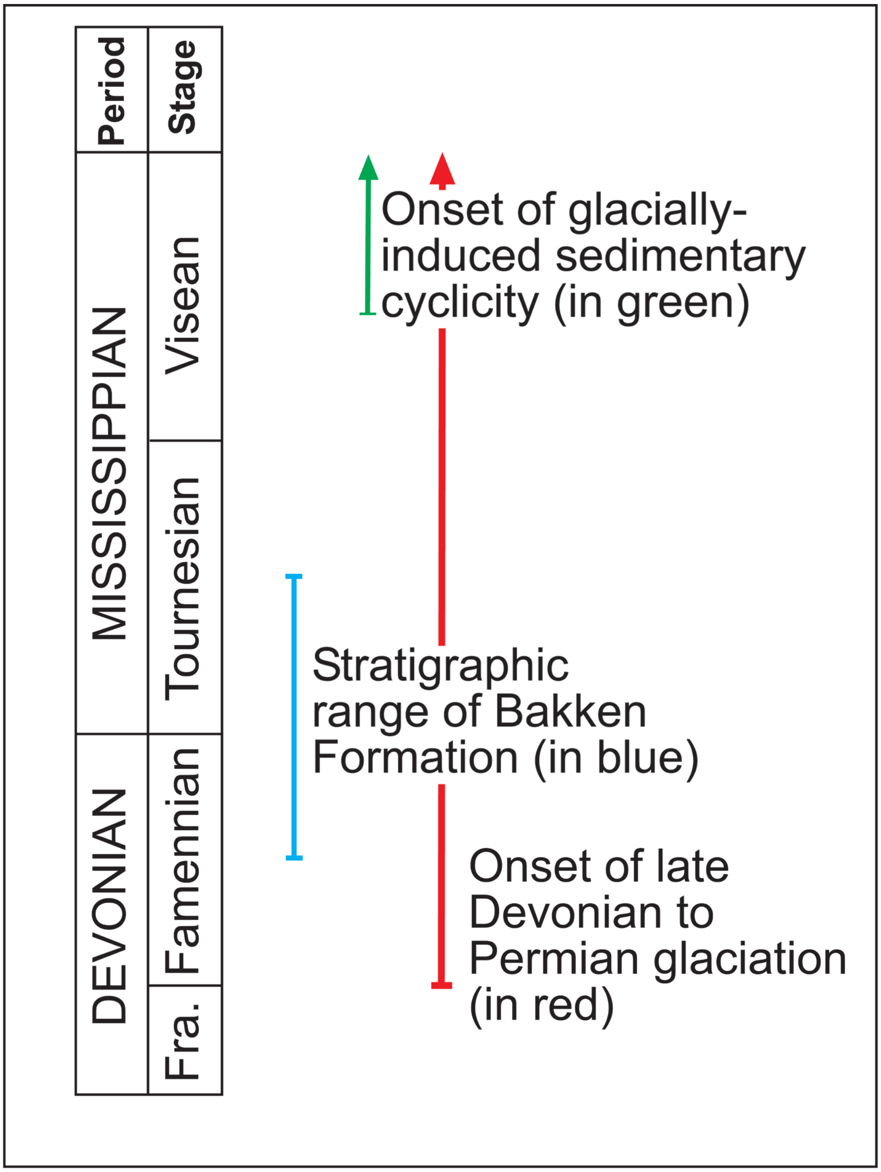

Figure 4: Schematic diagram of Bakken Formation age (blue) based on conodont data, the extent of the Devonian-Permian glaciation (red), and the onset of glacially-induced cyclicity (green). The diagram shows that Bakken deposition occurs before the onset of recognizable glacially-induced cyclicity in sediments worldwide. Fra. = Frasnian

properly is the recognition of several key parameters that can be gleaned by close examination of the rocks, both in core and in thin section. First, the SP points to initiation of Bakken deposition recording both regressions and transgressions (LeFever et al. 2011), and not the LBS as stated by Hart and Hofmann (2020). Secondly, the UBS demonstrates ample evidence of deposition from storms as well as significant bioturbation, despite their high TOC contents, which points to overturning the paradigm of deposition in waters well below storm wave base and under persistently anoxic conditions (e.g., Sonnenberg and Pramudito 2009), or even under euxinic conditions (e.g., Scott et al. 2017). Together, these parameters indicate that bottom currents were quite active and at least some degree of oxygenation persisted at the sediment/water interface during deposition of the LBS and the UBS (Albert 2014; Egenhoff and Fishman 2013; Borcovsky et al. 2017). Thirdly, the MB is characterized by abundant parasequences, each of them showing a flooding surface at both the base and the top which is likely driven by a series of transgressions and regressions throughout MB deposition (Egenhoff et al. 2011). Furthermore, some MB lithofacies, including ooid grainstones, were not deposited in a time-equivalent manner across the basin as evidenced by stacking patterns. Indeed, a depositional environment can establish itself in many different places in the basin based on sea-level changes and always produce a similar facies, but it is not sound to simply map similar facies and ascribe time equivalency to them (e.g., Hart and Hofmann 2020).

Sequence stratigraphic models must be constrained by a detailed sedimentological and bio- or chronostratigraphic framework (Catuneanu 2005). Below bio- or chronostratigraphic resolution, parasequence boundaries can be carefully traced through a basin and allow recognizing time-equivalency also for rocks of varying facies. Based on such models the Bakken shows (1) the lateral transition of shales into carbonates, and (2) a varying number of parasequences throughout the basin with more near the basin center and fewer towards the margins (Egenhoff et al. 2011; Borcovsky et al. 2017; Novak et al. submitted). This indicates that intracratonic basins adhere to sequence stratigraphic principles yet show geometries at incredibly low angles that are only visible when carefully correlating parasequences through a basin.

Although the Carboniferous-Permian glaciation is known to have commenced in the Late Devonian (e.g. Isaacson et al. 2008) the influence of glacially-induced sea-level changes on sedimentation seems to be only recorded in sediments from the upper Viséan on (Fielding and Frank 2015). A direct influence of the ice age on cyclicity in the Bakken, which was deposited near the paleoequator, therefore remains highly questionable.

CONCLUSIONS

The Bakken Formation consists of shallow-marine coarse-grained sediments to offshore organic-rich shales arranged in very gentle geometries equivalent to a nearly horizontal basin floor. The Bakken is organized into 5 sequences, which in turn consists of several parasequences. In regressive strata, their numbers increase from proximal to distal reflecting the successive exposure of the basin margin as sediment wedges step basinwards. Geometries in these strata are so gentle that they are only well recognizable in basin-wide transects. Nevertheless, regressive strata also show the black shales of the UBS transitioning into carbonates of the overlying Lodgepole Formation. The shales themselves exhibit evidence of burrowing and mudstone ripples and are interpreted to be deposited in an oxygen-deficient environment, subjected to common current activity. Finally, the high-amplitudes of sequences relative to the low-amplitude of parasequences make it unlikely that glacially-induced cyclicity governed sedimentation of the Bakken.

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