The Late Devonian Ice Age and the Giant Bakken Oil Field

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ABSTRACT

The physical stratigraphy of the North American Bakken Petroleum System, in particular the Middle Bakken Member, suggests that it formed in response to eustatic fluctuations around the Devonian-Mississippian boundary. Elsewhere, in North America and globally, time-equivalent strata have stratigraphic architectures interpreted to have been linked to glacioeustacy. The Gondwanan continental glaciations responsible for the eustatic fluctuations were, at least in part, driven by changes in atmospheric composition and colonization of continental interiors by land plants over 360 Ma. This paper links global climate fluctuations to petroleum systems.

INTRODUCTION

Links between changes to atmospheric composition, climate, and sea level are firmly established (e.g., Fairbanks, 1989; Petit et al., 1999; Joachimski and Buggisch, 2002), and there is much interest in relationships between fossil fuel consumption, atmospheric CO_2, greenhouse warming and rising sea levels. In this paper we suggest that deposition of the Bakken Formation, one of the world's 50 largest oil accumulations (Gaswirth et al., 2013), was driven by glacioeustacy and changes in atmospheric composition at the end of the Devonian. Our interest in the Bakken was initially spurred by reservoir characterization efforts in support of hydrocarbon development (Li et al., 2015; Edwards et al., 2016), but scientific curiosity led us to appreciate these broader links between the Bakken Petroleum System and global climate.

THE BAKKEN PETROLEUM SYSTEM

The Bakken Petroleum System is in the Williston Basin of central North America (Fig. 1A). We focus here on two critical petroleum system elements present within that system: source and reservoir rocks. The Lower Bakken Shale (LBS) and Upper Bakken Shale (UBS) are the primary organic-rich source rocks that expelled hydrocarbons into the adjacent Middle Bakken (MB) reservoir (Fig. 2). This type of direct juxtaposition of world-class source and reservoir rocks is not common, especially when source rocks are marine shales and reservoirs are shallow-marine clastic reservoirs as described below.

BAKKEN STRATIGRAPHY

The stratigraphy, sedimentology, and geochemistry of the Bakken have been discussed and debated by many authors previously (e.g. Smith and Bustin, 1998; Kohlruss and Nickel, 2009; Egenhoff et al., 2011; Angulo and Buatois, 2012; Egenhoff and Fishman, 2013; Scott et al., 2017; Sonnenberg et al., 2017). Despite this work, there is no consensus about environments of deposition (e.g., water depths or paleo-redox conditions during shale deposition) or the internal stratigraphic architecture of the Middle Bakken. Instead of summarizing and attempting to reconcile these different views, we highlight some specific aspects of the stratigraphy that we believe to be most germane to understanding the forcing mechanisms for Bakken deposition and summarize our sedimentologic interpretations that are broadly consistent with those of Smith and Bustin (1998), Kohlruss and Nickel (2009) and Sonnenberg et al. (2017).

The intracratonic Williston Basin was close to the equator (Fig. 1B) during Bakken deposition. Deposition spans 12 conodont zones (~ 8 to 10 MY) with the LBS being Upper Devonian (Famennian) and the UBS being Lower Mississippian (Tournaisian) (Hogencamp and Pocknall, 2018; Fig. 1C). To date, no reliable biostratigraphic or chronostratigraphic data have been retrieved from sandstones and siltstones of the MB. This absence of bio- or other chronostratigraphic evidence in the MB makes it impossible to accurately define the ages of the stratigraphic contacts between it and the adjacent shale members, or the ages of stratigraphic surfaces within.

The three primary members (the LBS, MB and UBS) can be mapped over approximately 150,000 km^2 using wireline logs and core (Fig. 2B). The LBS and UBS consist of organic-rich, structureless or laminated, siliceous, marine black shales having a total organic content that

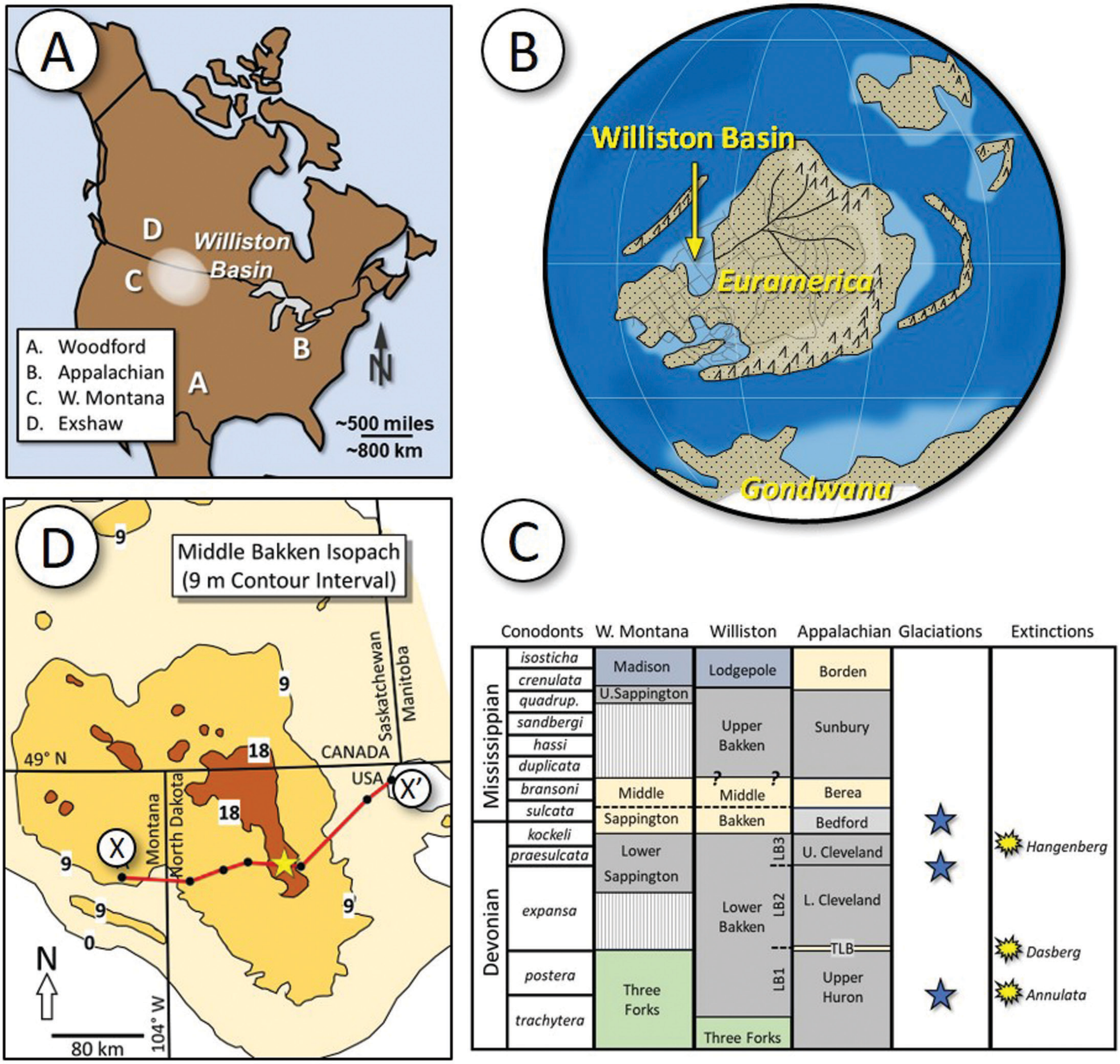

Figure 1: Clockwise from upper left. A) Base map showing present-day geography and locations of selected Devonian-Mississippian sections referred to in the text. B) Simplified Late Devonian paleogeography showing the location of the Williston Basin and location of continental ice in Gondwana. C) Stratigraphic correlations between western Montana (di Pasquo et al., 2017), Williston Basin (Hogankamp and Pocknall, 2018), northern Appalachian Basin (Algeo and Rowe, 2012). TLB – Three Lick Bed, the distal expression of a prograding succession in the northern Appalachian Basin (Ettensohn et al., 2009). Gondwanan glaciations from Isaacson et al. (2008) and extinction events from Kaiser et al. (2015). D) Isopach map of the Middle Bakken showing location of type log (yellow star) and cross section in Figure 2.

commonly ranges between 10 - 15% (Fig. 2A) (e.g., Hart and Steen, 2015; Sonnenberg et al., 2017). Redox-sensitive trace elements, such as molybdenum, are enriched in these shales (Fig. 2A; Hogencamp and Pocknall, 2018). The shales were mostly deposited below storm wave base that generally had anoxic to euxinic bottom (pore) waters (Scott et al., 2017; Browne et al., 2019), although sedimentologic data do not support persistent anoxia (Borcovsky et al, 2017).

In contrast, MB reservoir rocks were deposited in a shallower-marine setting than the shales (e.g., Smith and Bustin, 1998; Angulo and Buatois, 2012; Sonnenberg et al. 2017). These can be subdivided into three genetically related facies assemblages bounded by regionally significant surfaces, i.e. systems tracts MB-1 to MB-3 (Fig. 2A,B).

Middle Bakken Unit 1 (MB-1) is the lowest of the three systems tracts. It is sharply based with organic rich shales of the LBS overlain by bioclastic muddy siltstones (Figs. 2A,B, 3A). This type of abrupt facies transition and stratigraphic juxtaposition is characteristic of a regressive surface of marine erosion ("forced regression") as previously noted by Smith and Bustin (1998). Where fully developed, the overlying MB-1 interval represents an upward coarsening succession from bioclastic muddy siltstones to laminated siltstones (Figs. 3 A-C). We interpret this facies stacking as the result of progradation of a low-energy strandplain which, based on subsurface mapping (Fig. 1D), filled the entire Williston Basin.

The MB-1 is capped by a regionally mappable erosion surface we call the Middle Bakken Unconformity (MBU; Fig. 2A,B). Over much of the basin, cores show the MBU as separating the previously described low-energy strandplain deposits of MB-1 from overlying laminated and cross-bedded, fine- to medium-grained, calcareous sandstones (including bioclastic sandstones and oolites) that are locally contorted (Figs. 3D-I). These latter rocks are part of our Middle Bakken Unit 2 (MB-2) (Fig. 2). MB-2 is not present everywhere in the basin (Kohlruss and Nickel, 2009; Sonnenberg et al., 2017), but where present the grain size and sedimentary structures indicate deposition occurred under much higher energy paleonvironmental conditions than the underlying MB-1. Around some parts of the basin margin, the MB-2 rests unconformably on the Three Forks Formation (Figs. 2B, 3G). Like Kohlruss and Nickel (2009), we interpret the abrupt facies change between MB-1 and MB-2, and the substantial erosion observed on the MBU as indicative of another regressive surface of marine erosion. We postulate that MB-2 represents a second phase of forced regression, perhaps relatively short-lived, in a

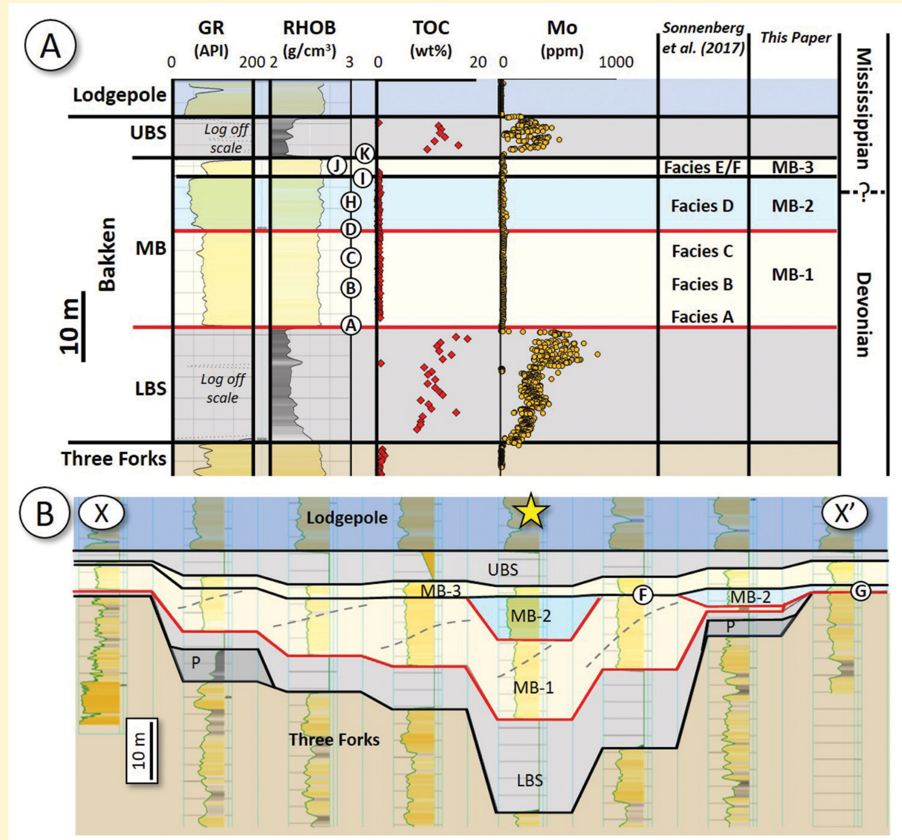

Figure 2: A) Type log for the Bakken in North Dakota showing stratigraphic units defined in the text and relationship between our stratigraphic terminology and that of Sonnenberg et al. (2017). B) Interpreted east-west gamma-ray log cross section through the Williston Basin (location in Figure 1C). All wells on the section are cored through the entire Bakken, enabling confident assignment of facies and surface picks. Yellow star in Part B shows location of Type Log shown in 2A. Lettered circles (A-K) show location of photos in Figure 3.

low-accommodation setting.

An abrupt change in grain size and lithology – interbedded mudstones, siltstones, and fine-grained sandstones (Fig. 3J) – accompanied with changes in sedimentary structures, higher bioturbation, and fossil content (e.g., brachiopods and crinoids; Fig. 3K) marks the contact between MB-2 and MB-3. This contact is mappable across the basin and is interpreted as a regional marine flooding surface. Locally, it is clearly associated with erosion of underlying strata (Fig. 3I). Where MB-2 is absent, this flooding surface amalgamates with the MBU (Figs. 2B, 3F). MB-3 is interpreted as the first deposits of a stepwise deepening environment with lower energy depositional conditions that culminated in the deposition of the UBS.

The black shales of the UBS are separated from the brachiopod-bearing siltstones of the underlying MB-3 along a sharp, but burrowed, contact. This surface is recognized everywhere in the basin and is interpreted as a regional flooding surface (Fig. 2A,B).

MIDDLE BAKKEN ACCOMMODATION CYCLE AND SYSTEMS TRACTS

Different styles of shoreline progradation occur in response to varying conditions of increased sediment supply and/or a change in base level, the latter being a function of both local subsidence/uplift and eustacy. The MB sedimentology and stratigraphy indicate that it represents deposition during a relative lowstand of sea level. Both MB-1 and MB-2

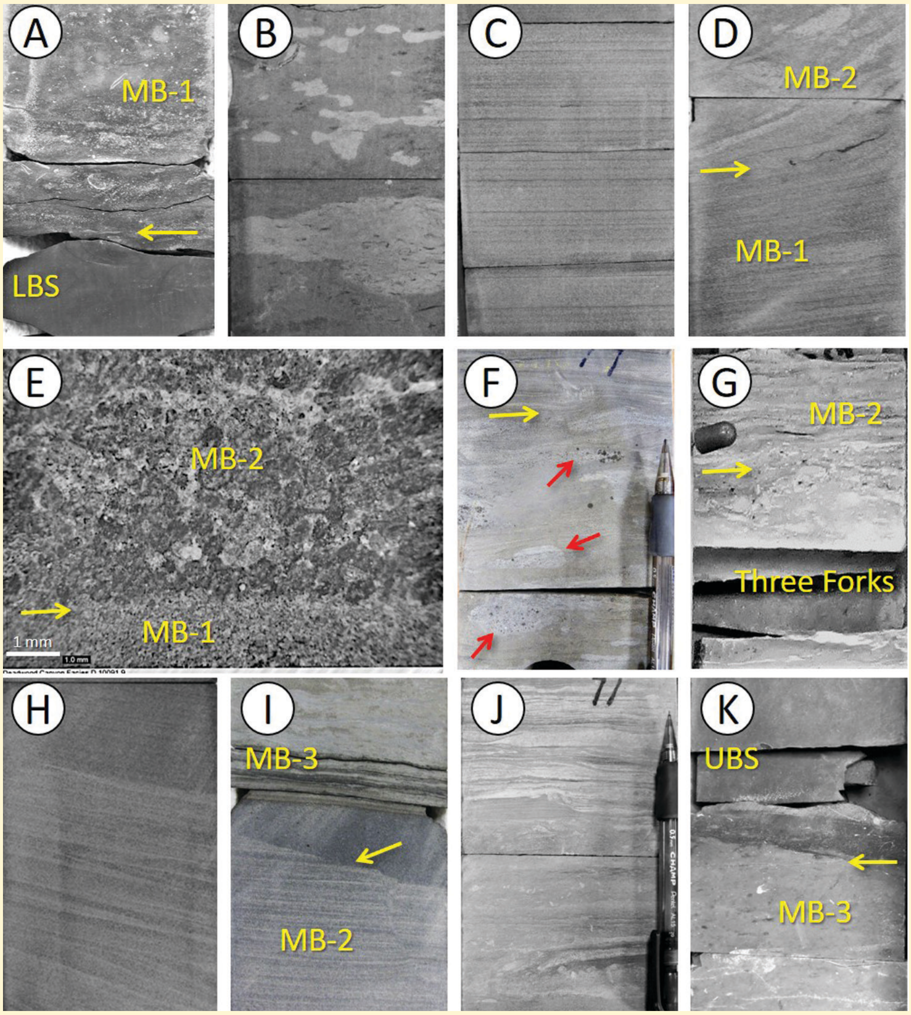

Figure 3: Middle Bakken core photos. All (except for Parts G, I, K) are from a core taken from well shown in Figure 2A; letters on that figure show photo locations. A) Burrowed contact between the LBS and MB shown by yellow arrow. B) Pervasively bioturbated muddy siltstones. Light-grey areas represent patchy calcite cementation. C) Laminated very fine- to fine-grained sandstones. D) Erosive sand-on-sand contact (yellow arrow) of the MBU is subtle but corresponds to a distinct grain-size break and change in sedimentary structures. E) MBU (yellow arrow) in a core taken close to type log showing ooids (MB-2) overlying laminated sandstone. F) Sand-on-sand contact (yellow arrow) of the MBU. Ooids are absent above the contact but fill burrows below it. G) The MBU (yellow arrow) in this core separates MB-2 from the underlying Three Forks Formation. H) Crossbedded medium sandstone of MB-2. I) Erosive nature of the contact (yellow arrow) between MB-2 and MB-3. J) Laminated, rippled and bioturbated siltstones in MB-3. K) Flooding surface (yellow arrow) between MB-3 and the UBS.

are underlain by regressive surfaces of marine erosion and capped by flooding surfaces. As such, in systems tract terminology, they represent falling-stage systems tracts. MB-3 is bound by flooding surfaces at its base and top and represents a transgressive systems tract.

Sea level drops, such as those inferred above, can be caused by either a eustatic drop or crustal uplift. Cratonic basins are typically characterized by broad, steady subsidence (e.g., Allen and Armitage, 2012) and Kuhn et al. (2012) suggested that the Williston Basin was undergoing a period of enhanced subsidence at the time of Bakken deposition. As such, we argue that eustatic forcing is a more likely driving mechanism for generating this forced regression than crustal uplift.

Unfortunately, the lack of biostratigraphic control for the MB makes it problematic to tie facies changes and surfaces of the MB to global events with precision. If eustacy was the primary control on facies stacking and surface development in the MB, there should be evidence of broadly time-equivalent sea level changes (i.e. lowstands) elsewhere and/or clear evidence for a driving mechanism.

THE BAKKEN IN A GLOBAL CONTEXT

Although the Devonian is commonly referred to as the Age of Fish, it could equally well be known as the age in which land plants colonized continental interiors. At the beginning of the Devonian, terrestrial vegetation was dominated by small herbaceous plants that were mostly constrained to living in moist lowland habitats (Algeo and Scheckler, 1998). The colonization of continental interiors by forests through the Middle to Late Devonian led to a drawdown in atmospheric CO_2 (Berner, 2004). Burial of organic carbon in Middle to Late Devonian black shales possibly also played a role, with a global spike in organic carbon burial being associated with the Late Devonian Hangenberg Black Shale of Europe and time-equivalent black shales elsewhere (Becker et al., 2016; Kaiser et al., 2016). Atmospheric O_2 approximately doubled, and CO_2 concentrations dropped from approximately 10 – 15 times modern levels in Early Devonian time to near modern levels by the end of the Mississippian (Berner, 2004). The draw down in atmospheric CO_2 levels led to global cooling and, eventually, to continental glaciation in Gondwana (Fig. 1B)(e.g. Caputo et al., 2008; Isaacson et al., 2008; Streel et al., 2013). The presence of glaciogenic deposits at relatively low latitudes such as the US Appalachian Basin (e.g., Ettensohn et al., 2009; Brezinski et al., 2010) indicates that cooling was indeed global in extent.

The buildup of a continental ice sheet in Gondwana lowered global sea level by 60-100 m (Isaacson et al., 2008; Brezinski et al., 2010; Kaiser et al., 2016). These estimates are broadly consistent with estimates of sea level fall during the Pleistocene glaciations (e.g., Shackleton, 1987), implying the Devonian ice buildup was potentially similar in scale. Scott et al. (2017), based on trace elemental studies, suggested that deposition of the LBS and UBS occurred within the photic zone, but below wave base, approximately between 100-150 m water depth. Egenhoff and Fishman (2013) and Borcovsky et al. (2017) also suggested deposition of the UBS below wave base but argued that bottom-water anoxia was not permanent. The formation of the regressive surfaces of marine erosion at the base of MB-1 and MB-2, and synchronous development of erosion surfaces along the basin margins, implies a change in sea level in the Williston Basin of many 10s of meters, in agreement with the proposed global changes.

Hogancamp and Pocknall's (2018) compilation of biostratigraphic data allows us to tie our inferred sea-level history for the Bakken to other North American basins and global events (Fig. 1C). Differences in tectonic settings (e.g., foreland basins versus intracratonic basins and associated changes in subsidence patterns and rates), depositional systems (e.g., carbonate vs siliciclastic, deep-water vs shallow-water) and other factors clearly influenced the preserved stratigraphic record (lithology, ages of surfaces, etc.) from basin to basin such that one-to-one lithostratigraphic correlations are not always present. Nevertheless, the available data allow us to make a few interpretations.

Initial flooding of the Williston Basin recorded in the deposition of the organic-rich LBS is partly or wholly correlative with flooding in some other North American basins, but not outside of North America. This suggests that the flooding recorded in the LB was probably driven by forces limited to this continent, including enhanced subsidence in the Williston Basin. Deposition of the organic-rich LBS began with a flooding of the Williston Basin in the *trachytera* conodont zone (Hogencamp and Poknall, 2018; Fig. 1C). This flooding significantly predates deposition of the Hangenberg Black Shale (*praesulcata* conodont zone) and time-equivalent black shales from other parts of the globe (Kaiser et al., 2016), although Hogencamp and Poknall (2018) correlated the molybdenum-enriched uppermost portion of the LBS (their LB3; Figs. 1C, 2A) to the Hangenberg Black Shale. In North America, the LBS is partly or wholly correlative to the Lower Sappington Shale of western Montana (e.g., Phelps et al., 2018), the Exshaw Shale in Alberta (Hartel et al., 2014), and the Cleveland Shale and equivalent units in Appalachia (e.g., Algeo et al., 2007; Fig. 1C). The basal MB erosional surface, bracketed by the *expansa* and *sandbergi* conodont zones (Hogencamp and Poknall, 2018), is the most distinct evidence of a significant base-level drop in the Bakken.

Because incised valleys, subaerial unconformities, karst and other erosion features (see compilation of Kaiser et al., 2016) have been described globally within the same condont zones, we link initial forced regression of the MB to this significant eustatic drop. In North America, the MB progradation closely correlates to deposition of the Middle Sappington, Exshaw Silt, Berea Sandstone and other regressive units (Algeo et al., 2007; Hartel et al., 2014; Phelps et al., 2018; Fig. 1C). It corresponds an erosional lacuna and distinct facies change in the Woodford Shale (Over, 1992). Assuming a seafloor slope of 0.02° for the Williston Basin (measured from bathymetric maps from the Gulf of Carpenteria, a modern epicontinental sea) a eustatic fall of 100 m would have caused shorelines around the basin to prograde inward up to 290 km whereas a 60 m fall would have caused the shoreline to migrate inward approximately 170 km from all sides of the basin. Either scenario would have at least drained the US portion of the Williston Basin and probably most of the Canadian portion.

The presence of multiple regression surfaces, the MBU at the base of MB-1 and the second forced regressive surface at the base of MB-2, could also be controlled by global ice sheet dynamics. Streel et al. (2013) noted that the Late Devonian glaciation may have consisted of multiple glacial-interglacial cycles, which may account for multiple MB surfaces. Unfortunately, and as noted by other authors before us (e.g., Sandberg et al., 2002; Kaiser et al., 2016), the biostratigraphically barren nature of MB and time-equivalent coarse-grained paralic deposits elsewhere currently makes this hypothesis untestable.

The initial demise of Late Devonian Gondwanan continental glaciations is first represented by the MB-3 transgressive systems tract with melting corresponding to a eustatic highstand and deposition of the UBS in the Lower Mississippian. Although the timing of that flooding and the amount of time missing (if any) at the contact between the two members remain unresolved, the UBS is at least partly correlative to the Upper Sappington Shale in Montana (Phelps et al., 2018), the Lower Banff Formation (a shale) in Alberta (Hartel et al., 2014), the Sunbury Shale in Appalachia (Algeo et al., 2007; Fig. 1C), and appears to partly correlate to the Lower Alum Shale in Europe (Babek et al., 2016).

CONCLUSION

Future work should test the main hypothesis put forth here that Late Devonian Gondwanan glaciation drove global sea level changes recorded in the Bakken. We emphasize that although these correlations to global events are consistent with the stratigraphic architecture of the Bakken and the latest biostratigraphic interpretations, they are not proven by them. Furthermore, parts of our narrative have been proposed before, such as the forced regressive character of the MB (e.g., Smith and Bustin, 1998) and correlation of the MB to the Berea Sandstone (e.g., Algeo et al., 2007) among others. Additionally, evidence for late Devonian glaciation from South America has been tied to global sea level changes (Isaacson et al., 2008). Our goal here has been to synthesize our stratigraphic observations of the Bakken with data and interpretations from other basins into an interpretation that is consistent with available data and explains the unusual juxtaposition of source-rocks and shallow-marine reservoir rocks in the Bakken, which was deposited in a relatively tectonically quiescent intracratonic basin. Future bio- or chemostratigraphic work could either falsify or support our working hypothesis. Finally, our hypothesis of a glacio-eustatic forcing on Middle Bakken deposition predicts that similar stratigraphic architectures could have developed in intracontinental basins during other glacial episodes in the earth's past.

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