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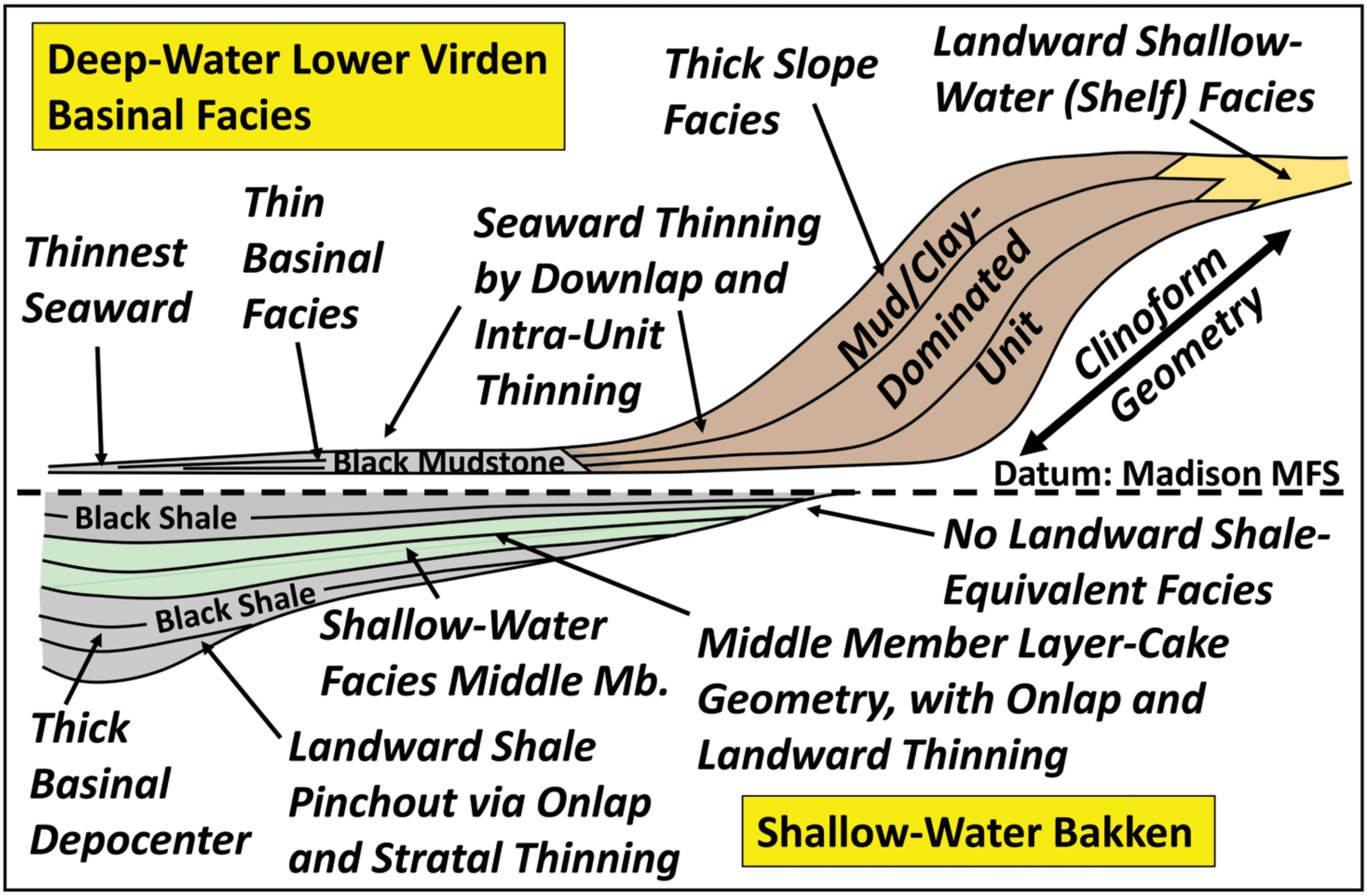

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Shallow-Water versus Deep-Water: Stratigraphic Geometries in the Organic-Rich Shale/Mudstone Debate

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ABSTRACT

In the central Williston basin, USA, the Bakken Formation and overlying lower Lodgepole Formation both have fine-grained, organic-rich stratigraphic units that have been interpreted sedimentologically to represent deep-water deposition in a low-energy, distal-marine environment; however, these formations display vastly different stratigraphic geometries that challenge the conventional sedimentology interpretations. The Bakken Formation spans the Devonian-Carboniferous boundary and includes black, organic-rich (2%–26% total organic carbon [TOC]) shale units. Stratigraphic characteristics strongly support deposition of all Bakken sediments in shallow water, as indicated by (1) the Bakken stratigraphic position overlying a major subaerial unconformity; (2) the restriction of Bakken strata to basinal areas; (3) the absence of shale-equivalent landward deposits; (4) a layer-cake, onlap, landward-thinning stratigraphic geometry for all Bakken units; (5) gradual landward shale pinchouts that occur by intra-shale onlap and stratal thinning, not erosional truncation; (6) unequivocal evidence for very shallow-water middle Bakken deposition; and (7) the absence of evidence for large intra-Bakken sea-level changes. Lower Lodgepole strata in the Williston basin are characterized by prominent sigmoidal clinoforms. In the lower Virden clinoform, argillaceous mudstone, laminated microcrystalline dolostone, microbial-peloidal-intraclastic packstone, and skeletal-oolitic limestone form a shelf facies that transitions seaward into a thick (maximum 80 m), skeletal-peloidal mudstone to packstone slope facies, which transitions seaward into seaward-thinning (10 m to 1 m), black, organic-rich (1%–8% TOC) carbonate mudstone in a basin-floor facies, inferred to have been deposited in water as deep as 140 m.

INTRODUCTION

There has been a +100-year debate over depth of deposition interpretations for fine-grained, organic-rich, upper Devonian–lower Carboniferous stratigraphic units in North America (Conant and Swanson, 1961; Ettensohn and Barron, 1981; McCollum, 1988), and this debate has accelerated in recent years. The upper Devonian–lower Carboniferous debate is part of a larger worldwide discussion on the origin of fine-grained, organic-rich stratigraphic units, as represented by session #144 at GSA Connects 2021, titled "Broken paradigms: Shallow-water deposition of organic-rich facies through Earth history" (Landing et al., 2021). Regional stratigraphic relationships that define shallow-water organic-rich depositional systems have recently been proposed for Devonian black shales in New York and suggested as a worldwide model for similar black shale depositional systems (Smith et al., 2019). Key shallow-water indications include onlap onto subaerial unconformities and the absence of a base-clinoform setting. However, the regional stratigraphic relationships for these black shales remain debated, and additional support data from comparable black shale stratigraphic systems is required to further define shallow-water relationships.

Research on upper Devonian–lower Carboniferous black shale units in the Bakken Formation in the North Dakota portion (Fig. 1) of the Williston basin illustrates the shallow-water versus deep-water

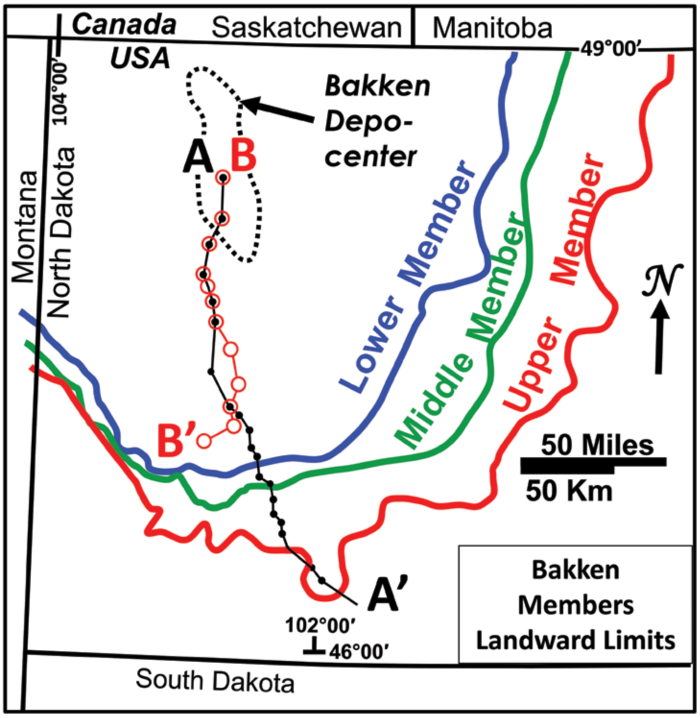

Figure 1. Landward limits for Bakken Formation members, with cross section locations.

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debate (see review in Petty, 2019a), with 66% of studies (61 out of 93) supporting deep-water Bakken deposition versus 34% of studies (32 out of 93) supporting shallow-water Bakken deposition. The debate continues, with Hart and Hofmann (2020) and Egenhoff and Fishman (2020) advocating for deep-water Bakken black shale deposition and Petty (2019a, 2021) advocating for shallow-water Bakken black shale deposition. Although paleontology, geochemistry, and worldwide-event studies contribute to this discussion, the essence of the argument is a sedimentology versus stratigraphy debate, with conventional sedimentology interpretations (e.g., fine grain size, clay content, laminations) suggesting deep-water deposition while stratigraphic observations (e.g., onlap onto subaerial unconformity and lack of landward-equivalent shallow-water strata) indicate shallow-water deposition. Recent studies suggest that sedimentology attributes are not unequivocal indicators of deep-water mud deposition (Schieber, 2016); thus, the stratigraphic geometry may be the ultimate arbitrator.

Although the Bakken Formation has been intensely studied, overlying stratigraphic units have received less attention. The term “false Bakken” has been applied to lower Lodgepole stratigraphic units or lithologies that superficially resemble organic-rich shale units in the underlying Bakken Formation. Most “false Bakken” designations refer to the basinal facies of the lower Virden subinterval, which lies a few meters above the top-Bakken in the basin-center, and this unit will be the focus of the Lodgepole study. To date, all studies (seven total) that offer an opinion on the origin of the organic-rich facies of the lower Virden conclude that it formed in a deep-water setting. As discussed below, this unit displays a dramatically different stratigraphic geometry from the Bakken Formation, and this contrast may offer evidence in the deep-water versus shallow-water debate.

STRATIGRAPHIC SETTING

The Madison 2nd-order sequence within the Williston basin was defined by Petty (2006), who placed the Bakken Formation in the transgressive systems tract and the Lodgepole Formation in the highstand systems tract (Fig. 2). Bakken strata lie on the Acadian unconformity (Fig. 2), which is characterized by sub-unconformity weathering near the basin-center (Bottjer et al., 2011) and extensive stratal truncation with deep sub-unconformity, paleokarst diagenesis in basin-margin areas (Petty, 2017, 2019a). The lower, middle, and upper members of the Bakken Formation display a regional onlap pattern defined by younger stratal units extending progressively farther landward than underlying stratal units (Meissner, 1978; Webster, 1984). Onlap is best displayed on the eastern to southern basin-flank (Fig. 1) where stable cratonic conditions persisted. Bakken deposition was followed by a major sea-level rise that formed the 2nd-order maximum flooding surface (Fig. 2) and flooded western North America, resulting in widespread epeiric conditions during early highstand deposition of lower Lodgepole sediments (Petty, 2019a, 2019b).

LITHOSTRATIGRAPHIC UNITS

Bakken lithostratigraphic descriptions are from wells in Figures 3 and 4, with mineralogy from Petty (2019a, table 1). The formation and member nomenclature of LeFever et al. (2011) is used for Bakken Formation units (Fig. 2). The gamma-ray character for lithostratigraphic units is illustrated with type logs in Figure 5. Pronghorn Member sediments were deposited on the Acadian unconformity in local depocenters with compositions reflecting erosion from local sources. Above the Pronghorn, all Bakken lithostratigraphic units can be correlated from the basin-center to the landward Bakken limit (Fig. 3). The Lower Member consists dominantly of black, faintly laminated to massive, organic-rich (7%–25% TOC from LeFever, 2008), high gamma-ray (250–1200 American Petroleum Institute [API] units), argillaceous (35% clay minerals),

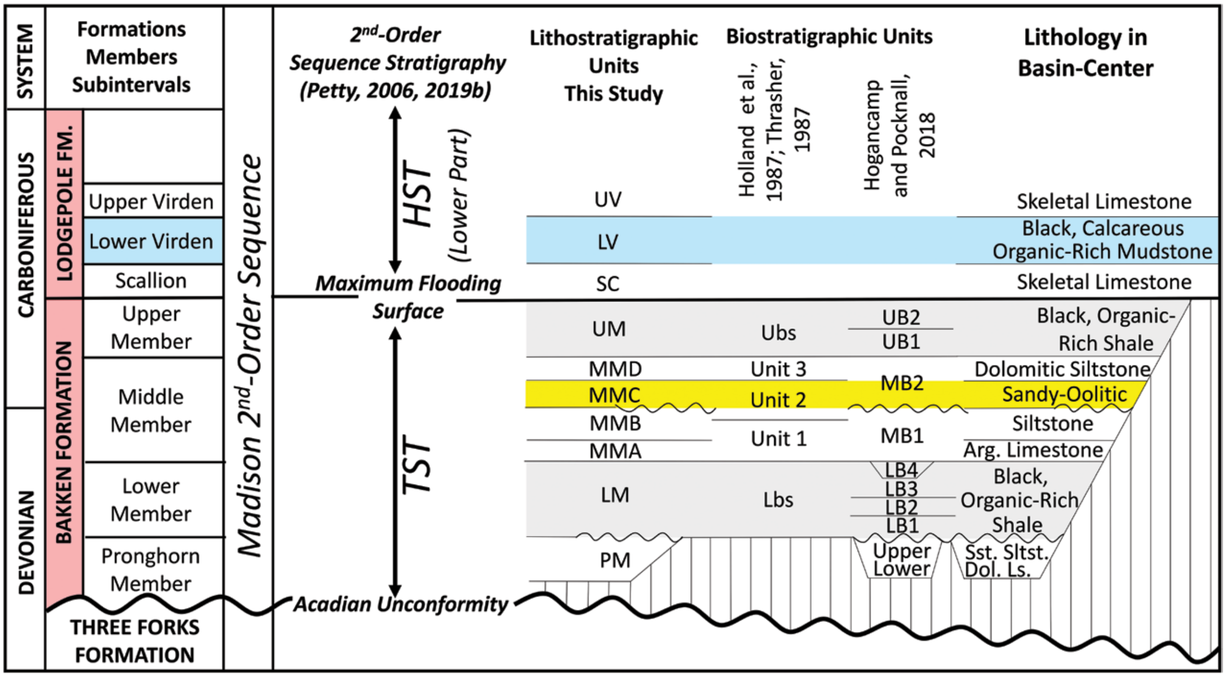

Figure 2. Stratigraphic column for the Bakken Formation and basal portion of the Lodgepole Formation. Arg.—argillaceous; Dol.—dolostone; Ls.—limestone; Sst.—sandstone; Sltst.—siltstone; HST—highstand systems tract; TST—transgressive systems tract.

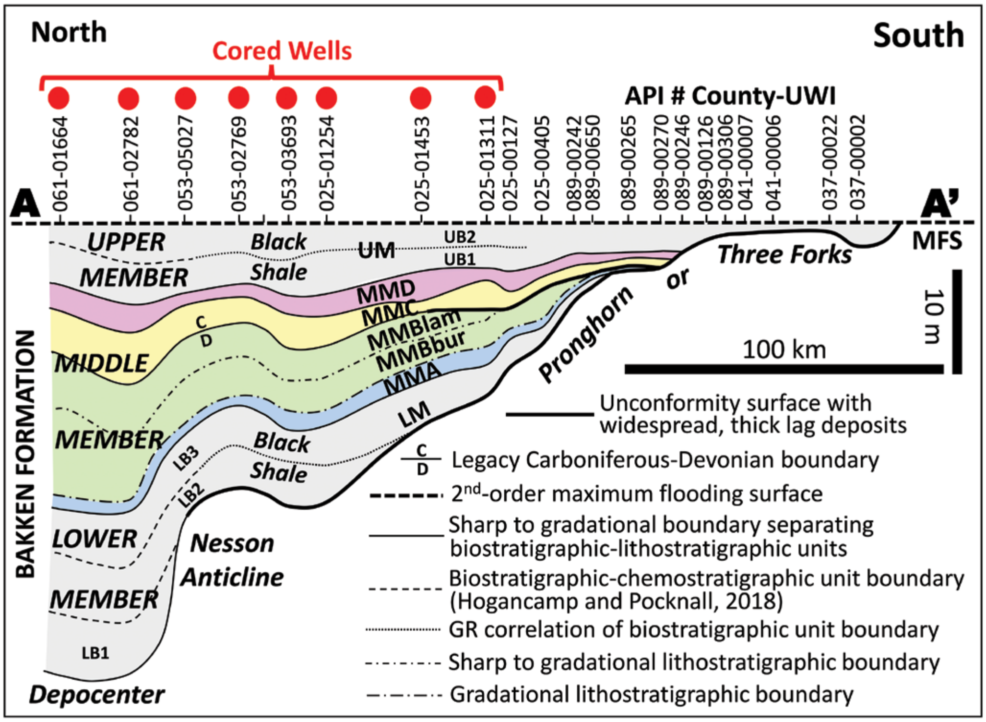

Figure 3. Cross section A–A′ showing correlation of Bakken lithostratigraphic units shown in Figure 2. Cross section location in Figure 1. GR—gamma ray; MFS—maximum flooding surface.

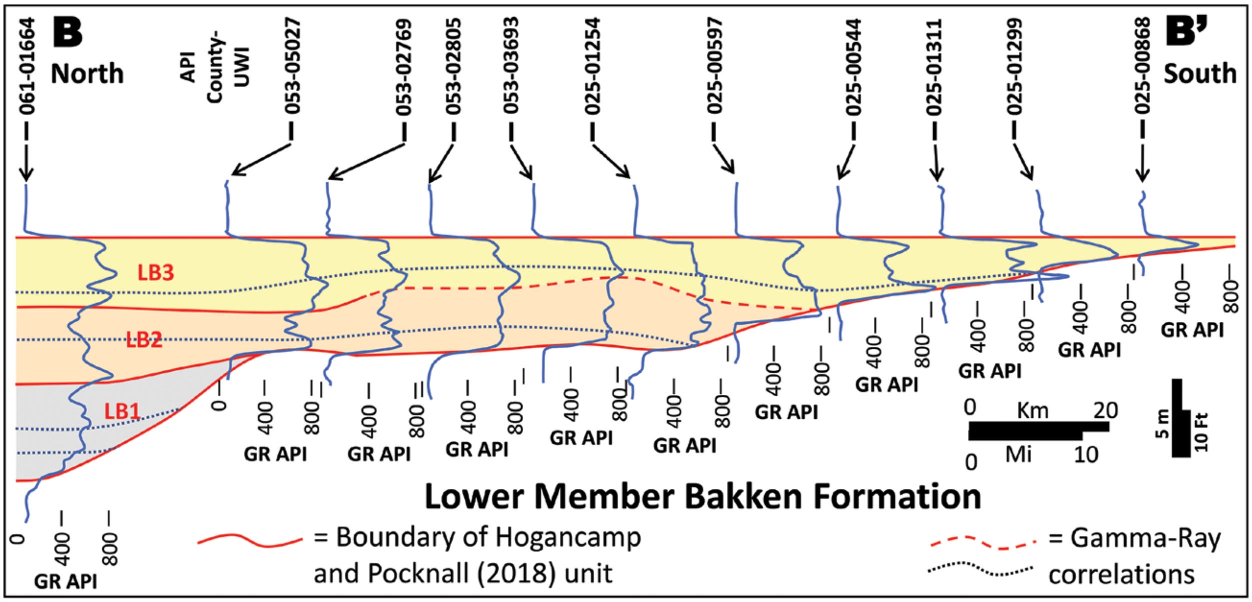

Figure 4. Cross section B–B′ shows lithostratigraphic-biostratigraphic-chemostratigraphic correlations for the Lower Member of the Bakken Formation for two seaward wells (from Hogancamp and Pocknall, 2018, fig. 5), and gamma-ray correlations for landward wells. Cross section location in Figure 1. API—American Petroleum Institute.

pyritic (7%), low-calcite (1%), silty shale. Cross section B–B′ (Fig. 4) shows a regional north-south correlation of the LB1, LB2, and LB3 subunits within the shale (see biostratigraphy below). This illustrates landward, intra-shale onlap with younger units extending progressively farther landward. The Middle Member A (MMA) lithostratigraphic unit consists of silty, burrowed, argillaceous limestone. The Middle Member B (MMB) lithostratigraphic unit consists of two facies: a lower bioturbated siltstone facies (MMBbur), and an upper laminated siltstone facies (MMBlam). The Middle Member C (MMC) lithostratigraphic unit is defined by a low gamma-ray response (Fig. 5) that represents the lowest clay content (4%) within the Bakken Formation. The

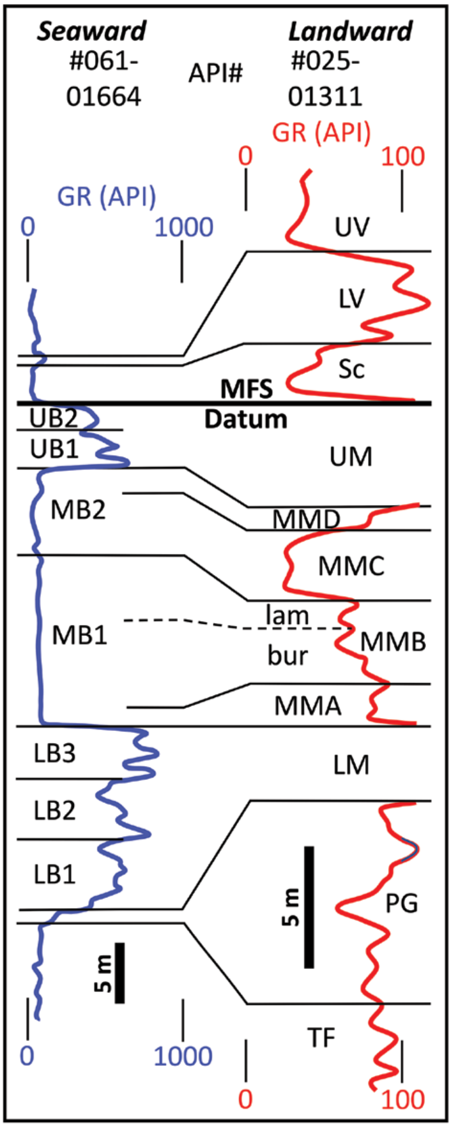

Figure 5. Type logs with gamma-ray character for lithostratigraphic units of this paper (right) and Bakken biostratigraphic units (left) of Hogancamp and Pocknall (2018, fig. 5). Logs represent the most-seaward and most-landward cored wells in Figure 3. Note that logs have different vertical scales (meters) and horizontal scales (API units). API—American Petroleum Institute.

presence of oolitic grainstone, skeletal-oolitic grainstone, sandy-oolitic grainstone, sandstone, and prominent cross stratification makes the MMC the most distinctive Middle Member unit. The Middle Member D (MMD) lithostratigraphic unit consists of argillaceous, dolomitic siltstone. The Upper Member consists dominantly of black, faintly laminated to massive, organic-rich (2%–26% TOC from LeFever, 2008), high gamma-ray (150–1100 API units), argillaceous (30% clay minerals), pyritic (6%), low-calcite (2%), silty shale that displays a layer-cake geometry regionally (Fig. 3).

Lodgepole lithostratigraphic descriptions are from locations in Figures 6 and 7. Log-defined units described in Manitoba by Stanton (1958) and carried through North Dakota by Grover (1996) are used within the Lodgepole Formation. The lower Virden subinterval is defined by a higher gamma-ray response than the underlying Scallion and overlying upper Virden subintervals (Fig. 6). Grover (1996) defined a clinoform geometry that was correlated throughout North Dakota where a thin (5–15 m) landward shelf facies transitions seaward to a thick (10–80 m) slope facies, which transitions seaward to a thin (1–10 m) basinal facies, as depicted in Figure 6. The lower Lodgepole clinoform geometry is illustrated in Grover (1996, figs. 14, 16, 18, 20, 22, and 33), Skinner et al. (2015, slide 12), Petty (2019a, figs. 10 and 11) and Figure 6 (this paper). In the Black Hills and the type area of Virden Field (Fig. 7), the shelf facies is characterized by skeletal-oolitic limestone, microbial-peloidal-intraclastic packstone, argillaceous mudstone, laminated microcrystalline dolostone, and thin stratiform breccias that represent former evaporite beds. The slope facies consists of brown to gray, massive to faintly laminated, argillaceous, medium gamma-ray (40–100 API units), organic-lean (0.4% TOC), silty, skeletal-peloidal, calcareous mudstone to packstone. The slope facies transitions seaward to the basinal facies that is confined to the center of the Williston basin (Fig. 7). This facies thins from 10 m or less landward to 1 m or less in the basin-center. Basinward thinning within the lower Virden is caused by downlap and stratal thinning. The basinal facies consists of gray to black, generally massive, locally laminated, moderately high gamma-ray (100–150 API units), organic-rich, sparsely skeletal, argillaceous (39% clay), calcareous (37% calcite), low-pyrite (1%), silty mudstone. TOC contents vary from 1.1%–5.3% for three samples from wells in Figure 6, to 5%–8% for mature samples in Price and LeFever (1994), equivalent to 7%–12% in immature samples.

BAKKEN BIOSTRATIGRAPHIC UNITS

Bakken biostratigraphy studies define stratigraphic units characterized by lithology, paleobiology, and chemostratigraphy. All of these are described as "biostratigraphic units" in Figure 2. The Lower Member of the Bakken Formation was subdivided into four lithostratigraphic-biostratigraphic-chemostratigraphic units in North Dakota by Hogancamp and Pocknall (2018); these were designated LB1, LB2, LB3, and LB4. These units display a regional, landward, intra-shale onlap pattern in a northeast-southwest profile (Hogancamp and Pocknall, 2018, fig. 4); the LB4 unit is present locally. The Middle Member lithostratigraphic units of this study (MMA, MMB, MMC, and MMD) either correspond with, or parallel, the Middle Member biostratigraphic units of Holland et al. (1987), Thrasher (1987), and Hogancamp and Pocknall (2018), as depicted in Figures 2 and 5. The Upper Member of the Bakken Formation was subdivided into two lithostratigraphic-biostratigraphic-chemostratigraphic

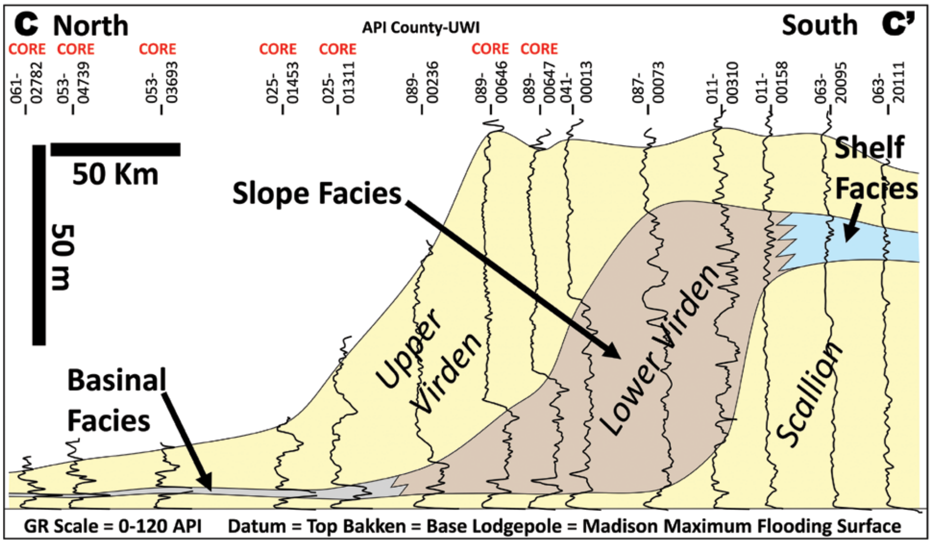

Figure 6. Cross section C–C′ showing lower Lodgepole stratigraphic relationships. Cross section location in Figure 7. API—American Petroleum Institute; GR—gamma ray.

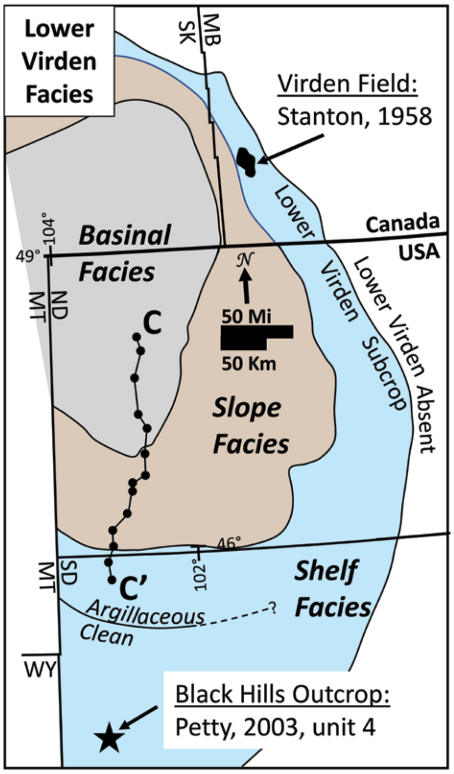

Figure 7. Lower Virden facies. Canada portion modified after Young and Rosenthal (1991). MB—Manitoba; MT—Montana; ND—North Dakota; SD—South Dakota; SK—Saskatchewan; WY—Wyoming.

units in North Dakota by Hogancamp and Pocknall (2018); these were designated UB1 and UB2. These units display a regional layer-cake pattern in a northeast-southwest profile (Hogancamp and Pocknall, 2018, fig. 4).

INTERPRETATION

Bakken Stratigraphic Geometry

The Bakken biostratigraphic units are regarded as "nearly isochronous" (Thrasher, 1987, p. 65). The parallelism or concordance between Bakken lithostratigraphic units and Bakken biostratigraphic units (Figs. 2 and 5) strongly indicates that all Bakken lithostratigraphic units represent layer-cake, near-isochronous deposition. The Bakken lithostratigraphic units (Fig. 2) define a landward-thinning, onlap geometry (Fig. 3) for the lower, to middle, to upper members of the Bakken Formation. Additionally, intra-shale lithostratigraphic-biostratigraphic-chemostratigraphic correlations (Hogancamp and Pocknall, 2018) and intra-shale gamma-ray correlations (Fig. 4) define an intra-shale, onlap geometry, with landward thinning at the pinchout edge.

There is no evidence via gamma-ray correlations or biostratigraphy that the Bakken black shales transition landward into any other lithology, an observation acknowledged by many deep-water advocates (Caplan and Bustin, 1998; Smith and Bustin, 2000; Egenhoff and Fishman, 2013). The intra-shale, onlap stratal geometry, and gradual landward thinning of the Lower Member black shale (Fig. 4) precludes the erosional-remnant interpretation for the Lower Member because the long-distance correlation of intra-shale gamma-ray character indicates minimal intra-shale erosion within the Lower Member. The black shale of the Upper Member is interpreted to have undergone minimal truncation in the southern basin area based on the presence of uniform, landward stratal thinning (Fig. 3) and the absence of mappable truncation features.

Large intra-Bakken sea-level changes, possibly greater than 200 m, have been inferred (Smith and Bustin, 1995, 1996, 2000; Caplan and Bustin, 2001; Hart and Hofmann, 2020) based on the assumption that upper Member and lower Member black shale units formed in deep water, while middle Member strata formed in shallow water. However, no intra-Bakken stratigraphic geometries (e.g., mappable clinoforms, mappable back-step geometries, mappable progradational geometries, major onlaps, major offlaps, etc.) were documented that support large intra-Bakken sea-level changes. Conversely, the presence of oolitic limestone, stromatolites, paleosols, and root traces in the Middle Member C unit (Petty, 2019a, p. 59) is considered as unequivocal evidence for shallow-water Bakken deposition. The stratigraphic evidence indicates that Bakken black shale represents deposition in water depths of <30 m (Petty, 2019a, p. 62), and it is suggested here that the meager stratigraphic record for large intra-Bakken sea-level changes is, in fact, evidence for the absence of large sea-level changes.

Lower Virden Stratigraphic Geometry

The largest intra-Madison sea-level change is inferred to have occurred during the Madison maximum flooding event (Figs. 2, 3, and 6) that separated underlying Bakken deposition from overlying Lodgepole deposition. Smith (1977) and Petty (2019a) estimated this sea-level rise to be ~100 m in central Montana and the Williston basin. The basinal facies of the Scallion subinterval of the basal Lodgepole is estimated to have been deposited in a maximum water depth of 120 m (Petty, 2019a) based on Scallion clinoform thickness and compaction assumptions. Using similar assumptions for the lower Virden, the basinal facies is estimated to have been deposited in a maximum water depth of 140 m.

The most significant advancement in the understanding of the lower Virden regional stratigraphy within the Williston basin was the recognition and regional mapping of the lower Lodgepole clinoform geometry (Grover, 1996). The lower Virden clinoform is interpreted to represent shelf, to slope, to basinal depositional environments, and the corresponding facies are broadly referred to as the shelf facies, slope facies, and basinal facies (Figs. 6 and 7). The clinoform is defined by a thin (<15 m), landward shelf facies that transitions seaward into a thick (maximum 80 m) slope facies that transitions farther seaward into a thin (<10 m) basinal facies.

Beyond the clinoform geometry, the main defining stratigraphic characteristics for the lower Virden system are (1) the presence of a landward facies with definitive shallow-water lithologies that include oolitic grainstone, microbial grainstone and packstone, and solution breccia; (2) the seaward transition to finer-grained lithologies; (3) the seaward transition to more clay-rich lithologies; (4) the seaward transition to mudstone-appearing lithologies that probably represent compacted peloidal packstone; (5) seaward thinning within the slope facies by downlap and intra-unit thinning; (6) continued seaward thinning within the basinal facies; and (7) the thinnest development (<1 m) in the basin-center. Many of these characteristics are the opposite of those seen in the Bakken shallow-water system.

SUMMARY AND CONCLUSIONS

The shallow-water Bakken stratigraphic geometry below the Madison maximum flooding surface differs dramatically from the deep-water lower Lodgepole stratigraphic geometry above the Madison maximum flooding surface. Key stratigraphic geometry differences between the Bakken and lower Virden portion of the lower Lodgepole include:

1. The lower Virden has a well-defined lateral transition from the basinal facies, landward into the slope facies, and farther landward into the shelf facies, but there is no lateral transition from Bakken stratigraphic units into landward shallow-water

units because all Bakken stratigraphic units are shallow-water facies.

2. Bakken lithostratigraphic and biostratigraphic units are relatively uniform laterally, while there is great lateral lithostratigraphic variability within the lower Virden.
3. The thickest Bakken development occurred in the basin-center, while the thickest lower Virden development occurred in the slope facies.
4. There are no mappable clinoforms within the Bakken; conversely, the clinoform geometry is the most conspicuous geometric feature of the lower Virden.
5. All Bakken stratigraphic units thin landward, while the “false Bakken” (lower Virden organic-rich, basinal facies) thins seaward.
6. Bakken lithostratigraphic units display prominent onlap, while overlying lower Lodgepole stratigraphic units display downlap or extreme basinward thinning.
7. Bakken Formation black shales pinch-out landward via intra-shale onlap and stratal thinning; conversely, lower Virden black mudstone thins seaward via downlap and stratal thinning.

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